MUSEUM LIGHTING WITH LIGHT EMITTING DIODESA CONCEPT FOR LIGHT DAMAGE MITIGATION AT THE RUAM SAMAI MUSEUM, CHIANG MAI, THAILAND

By
Miss Aurelia BERGER

An Independent Study Submitted in Partial Fulfillment of the Requirements
for Master of Arts Cultural Heritage Conservation and Management (International Program)
Silpakorn University
Academic Year 2024

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MissAurelia Berger

การค้นคว้าอิสระนี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรศิลปศาสตรมหาบัณฑิต

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By	Miss Aurelia BERGER
Field of Study	Cultural Heritage Conservation and Management (International Program)
Advisor	Dr. Thanya Lunchaprasith

Faculty of International College, Silpakorn University in Partial Fulfillment of the Requirements for the Master of Arts

.... Dean of Faculty of International College
(Assistant Professor Chombhak Klangrahad)

Approved by

.... Chair person
(Professor Dr. Gabriela Krist)

.... Advisor
(Dr. Thanya Lunchaprasith)

.... Committee
(Dr. Nethchanok Riddhagni)

.... External Examiner
(Dr. TATJANA BAYEROVA)

649020008 : Major Cultural Heritage Conservation and Management (International Program)
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Miss Aurelia BERGER : MUSEUM LIGHTING WITH LIGHT EMITTING DIODESA Concept for Light Damage Mitigation at the Ruam Samai Museum, Chiang Mai, Thailand Thesis advisor : Dr. Thanya Lunchaprasith

Museum Lighting with Light Emitting Diodes

A Concept for Light Damage Mitigation in the Ruam Samai Museum, Chiang Mai, Thailand

This thesis presents an approach to mitigate light damage in museums, focusing on the use of LED exhibition lighting at the planned Ruam Samai Museum (RSM) in Chiang Mai. The collection to be exhibited is composed of South-East-Asian antiques, modern and contemporary art. The research on the methodology of light- and UV-vulnerability categorisation of col- lections forms the basis for the assessment of light sensitivity of the RSM collection.

Further, the scientific foundations of object illumination in museums are elaborated, followed by a comparison of the benefits and disadvantages of conventional light sources and LEDs. The following chapter delves into light-induced deterioration processes. Examples of the degradation of colourants follow.

Solutions are presented for the control of natural and artificial light, in exhibition rooms and in showcases, based on the current discourse of literature. Finally, the thesis offers a compre- hensive and sustainable strategy for light damage mitigation at RSM.

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Institute of Conservation, University of Applied Arts Vienna

Co-supervision
Dr. Thanya Lunchaprasith
Silpakorn University International College, Silpakorn University

Co-supervision Conservation Univ.-Ass. Dr. Tanushree Gupta
Institute of Conservation, University of Applied Arts Vienna

Univ.-Ass. Mag.art. Carine Gengler MAS, BA
Institute of Conservation, University of Applied Arts Vienna

Co-supervision Natural Sciences Sen.Lect. Dr.rer.nat. Farkas Pintér
Institute of Conservation, University of Applied Arts Vienna

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Aurelia BERGER

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Introduction

In recent years with the challenges of climate change, preventive conservation has become an increasingly important field of conservation. "If a major portion of our heritage is to survive, it must be cared for collectively rather than individually. For the conservator this means focusing on ways of preventing or slowing the deterioration of objects through control of the collection's environment. It means, in short, preventive conservation."[1] By setting preventive protection measures, irreversible damage to the original structure of artworks as well as costly and time-consuming remedial conservation can be reduced and minimised.

Natural and artificial light are agents of deterioration that must be controlled in museums. This master thesis elaborates the development of a light damage mitigation concept for the light-emitting diode (LED) exhibition lighting system[2] of the Ruam Samai Museum (RSM) in Chiang Mai. This museum is housing a part of the Angsuvarnsiri family's private collection that contains over 6,600 pieces.[3]

The first part of this text focuses on the assessment of the light sensitivity of the RSM collection. The collection contains primarily South-East-Asian antiques, modern art, and contemporary art, is introduced. The methodology of assessing the light sensitivity of museum collections in this master thesis is based on the CIE 2004[4] publication, on the Getty Conservation Center/ Canadian Conservation Institute guidelines from 2012[5] by R. Druzik and S. Michalski and on D. Saunders "Museum lighting" from 2021[6]. The material groups of the RSM collection are classified according to their light sensitivity, especially sensitivity to ultraviolet radiation.

Then, scientific foundation of object illumination in a museum (lighting) context are elaborated. Physical principles are discussed. Conventional light sources used for exhibition lighting are compared with a focus on the benefits and disadvantages of LED lighting. Finally, the principles of measuring light and ultraviolet radiation are provided.

[1] Levin, Jeffrey, 'Preventive Conservation', *The Getty Conservation Institute Newsletter*, VII winter 1992, 4.

[2] This thesis focuses on light damage mitigation concepts for exhibition lighting only (A discussion on storage lighting is not included.).

[3] Sadakorn, Pornganok, 'Planning of a Storage Space in Ruam Samai Museum, Chiangmai, Thailand. Concept for Furnishing a Suitable Storage to Protect and Preserve Works of Art' (Master thesis, Bangkok, Silpakorn University, 2023), 6.

[4] CIE (Commission Internationale de l'Éclairage), *Control of Damage to Museum Objects by Optical Radiation*, CIE 157-2004 (Vienna: Commission Internationale de l'Éclairage, 2004).

[5] James R Druzik and Stefan W Michalski, *Guidelines for Selecting Solid-State Lighting for Museums* (Los Angeles/Ottawa: The Getty Conservation Institute, 2012) https://www.getty.edu/conservation/publications_resources/pdf_publications/pdf/solid-state-lighting.pdf.

[6] David Saunders, *Museum Lighting: A Guide for Conservators and Curators* (Los Angeles: Getty Publications,2021).

Moreover, a part of this thesis focuses on light damage processes. Photochemical and thermal changes are described, that can occur in objects when exposure guidelines are not followed. Possible light- and UV- induced damage phenomena are elaborated, and their description is supported by case studies.

Finally, the last part elaborates the most important factors that have to be considered to create a light damage mitigation system. The management and control of natural and artificial light sources are elaborated. Recommendations are given for a comprehensive and sustainable light damage mitigation concept for RSM, and light and ultraviolet radiation monitoring strategies are suggested.

1. Assessment of light sensitivity of the Ruam Samai Museum collection

1.1. Planning the Ruam Samai Museum

The Ruam Samai Museum (RSM) represents a novel institution within the realm of Thai art, serving as a repository for a subset of the Angsuvarnsiri family's collection. The museum project was initiated in 2018.

The building complex, which covers an area of 11.200 m^2,[7] is designed by studio MDA[8] and will open in 2026 in the centre of Chiang Mai.[9] The RSM will contain 3 exhibition buildings: The Contemporary Collection Exhibition Space (Fig. 1, orange building), the Private Collection Exhibition Space (Fig. 1, bright green building) and the Temporary Gallery Exhibition Space (Fig. 1, blue building). As a modern museum it will be a multi-functional facility, with a reading and screening room, black box, amphitheatre, outdoor café, event spaces and a workshop space. While the exhibition concept is still in planning phase, it has been decided that around 300 South-East Asian antiques and contemporary artworks will be permanently displayed there.

Figure 1: Plan of the RSM building complex, MDA Studio of architect Markus Dochantschi, 2018

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[7] Sadakorn, 'Planning a Storage Space', 5.
[8] MDA Studio of architect Markus Dochantschi.
[9] Sadakorn, 'Planning a Storage Space', 1.

The lighting plan in the exhibition spaces includes partial natural lighting. (windows) and artificial light sources (Fig. 2). RSM Management is planning to use LEDs adjustable[10] from 50 to 300 lux with UV-filter, that will be installed by Thai company Rangsi Atelier. It has not yet been decided which lamp type will be finally used.

Figure 2: The planned interior of the Contemporary Collection Exhibition Space.

The objects, that will be exhibited in RSM are currently stored in Bangkok (in the Angsuvarnsiri's temporary storage in Soi Sukhumvit 49, Bangkok[11]). It is scheduled to move them in the year 2024 to the newly planned storage building in Chiang Mai. The forth-coming museum storage facility will be built in Yu Yen Soi 3 in Chiang Phueak district, around 1 km from the museum building.[12] Finally, in the years 2025 and 2026 the objects will be moved to the RSM's three exhibition spaces.

1.2. Introduction to the collection

Subhashok and Jongsuwat Angsuvarnsiri have been centring collection efforts on South-East Asian (mainly Thailand, Myanmar, Laos), Indian and Chinese antiques (1500's-1900's). [13] Thai contemporary art since the 1990's, Thai modern art and international contemporary art are other collection focuses.[14] The Angsuvarnsiri's family collection consists of 6.686 objects.[15]

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[10] Most likely LEDs from ERCO company will be chosen, https://www.erco.com/en/.

[11] Sadakorn, 'Planning a Storage Space', 12.

[12] Sadakorn, 'Planning a Storage Space', 5.

[13] Sadakorn, 'Planning a Storage Space', 5.

[14] Pornganok Sadakorn, 'Collection Analysis for an Effective Planning of a Storage in Ruam Samai Museum, Chiangmai, Thailand', in *SUIC's 7th International Conference Proceedings: The Megatrends Shaping Art, Business and Technology* (Bangkok: Silpakorn University, Sanamchandra Campus, 2023), 160.

[15] Sadakorn, 'Collection Analysis', 167.

Furthermore, a museum database[16] has been established for the Angsuvarnsiri's collection in recent years (as state of May 2023).[17]

During the participation in the new joint master study programme Cultural Heritage Conservation and Management by the Institute of Conservation of University of Applied Arts Vienna and the International College (SUIC) of Silpakorn University Bangkok, student Pornganok Sadakorn and the author intended their master theses to focus on the application of state-of-the- art preventive conservation guidelines on the yet-to-be-built Ruam Samai Museum The collec- tion analysis and storage planning was performed by Pornganok Sadakorn in her master the- sis.[18]

The biggest material group in the Angsuvarnsiri's Private Collection are ceramic objects (29.40%), followed by metal objects with 27.76%. Paper objects, canvas paintings and wooden objects make up each around 12% of the total collection.[19]

Moreover, 2.77% of the collection are objects containing animal products. And finally, glass, stone, textile, plastic, and electronic exhibits make each just around 1 % or under 1 % of the total amount of objects (Fig. 3 on p.8).[20]

Most of the ceramic objects are Chinese blue and white ware (kitchenware), sculptures and coins. The metal object group of the Antiques Collection consists mostly of accessories, coins, sculptures, weapons, ceremonial objects, and kitchenware. Furthermore, most of the wooden objects are furniture, ceremonial objects, and miscellaneous objects.[21] Finally, there are about 840 canvas paintings in the collection.

Based on this classification of the collection in material groups and according to use[22], the assessment of light sensitivity of the RSM collection can be undertaken.

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[16] The RSM database uses Artlogic® Database software.
[17] Sadakorn, 'Planning a Storage Space', 181–83.
[18] Sadakorn, 'Planning a Storage Space', 40–47.
[19] Sadakorn, 'Planning a Storage Space', 144.
[20] Sadakorn, 'Collection Analysis', 8.
[21] Sadakorn, 'Collection Analysis', 171–72.
[22] Sadakorn, 'Planning a Storage Space', 143–45.

Private Collection 2023: Summary sheet 6,686 pieces
*update 08/05/2023

Summary	Type	Materials											Amount
		Animal Product	Canvas	Ceramic	Electronic	Glass	Metal	Paper	Plastic	Stone	Textiles	Wood	
	Antique	185	0	1963	0	63	1774	38	9	65	32	763	4892
	Thai Modern Art	0	463	0	0	0	68	277	0	0	0	5	813
	International Art	0	11	3	8	6	12	14	9	1	2	2	68
	Thai Contemporary Art	0	365	0	12	0	2	521	5	0	6	2	913
	Amount	185	839	1966	20	69	1856	850	23	66	40	772	6686

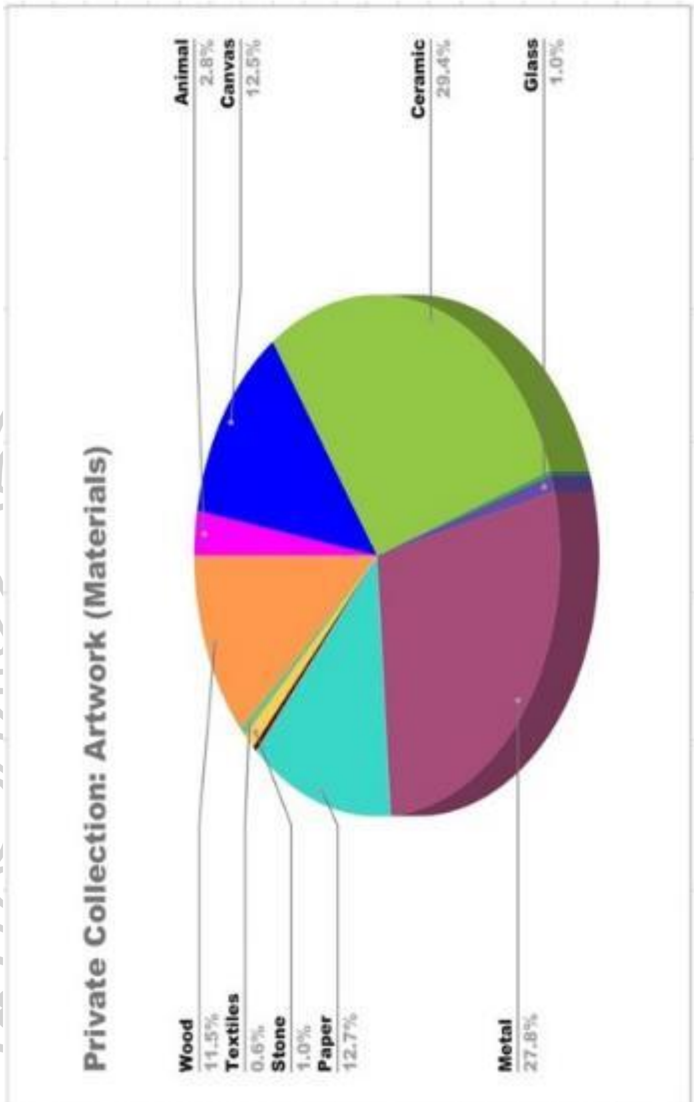

Figure 3: The number of objects per material group in the four sub-collections in form of a table and illustrated as pie chart (shares in percentages).

1.3. The methodology of assessing the light sensitivity of objects

Lighting system research from a conservation perspective is still a focus of museum research today. Light damage processes depend on the photochemical stability[23] of the object but also on the time while it is illuminated on display (= exposure time).

How exposure determines the damage potential of light

The longer these objects are exposed to light, the higher is the damage potential. The exposure of an artefact to light is a product of illuminance, which is the light level projected on a surface, and time. The unit of the illuminance is lux. "An illuminance of 1 lux (lx) is produced when a flux of 1 lumen is delivered across an area of 1 square metre." The following equation describes the relation between illuminance, time, and exposure.

Illuminance (lux) x Time (hours) = Exposure (lux hours)

Exhibiting an object for 1 hour at 100,000 lux (direct sunlight) is equivalent to exhibiting the object for 2000 hours at 50 lux (museum lighting).

100,000 lx	x	1 h	=	100,000 lx h
50 lx	x	2000 h	=	100,000 lx h

Both of these exposure times may cause light damage, but an illuminance of 50 lx allows for a far longer exhibition before damage occurs. When planning a permanent exhibition, it should be thus considered that reduction of illuminance (for instance dimming of light sources) can lead to longer display times.[24] Still, conservators must "deal with the fact that light-sensitive objects have finite display lifetimes and must seek to avoid unnecessary light exposure for such materials. This is part of the process of risk management (…)."[25]

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[23] Photochemical stability pertains to the resistance of a material to undergo chemical alterations when subjected to photonic exposure. This concept transcends mere chromatic stability; it encompasses the material's resilience against all forms of photochemically induced alterations (Saunders, '*Museum Lighting*', 94).

[24] Saunders, '*Museum Lighting*', 290.

[25] Terry T. Schaeffer, *Effects of Light on Materials in Collections: Data on Photoflash and Related Sources* (Los Angeles: Getty Publications, 2001), 1.

Classification methods

Any categorisation of light and ultraviolet radiation sensitivity is always a generalisation. It is the aim to classify museum objects in general sensitivity categories to receive an overview of the collection's sensitivity.[26]

Most light-sensitive materials are damaged primary by a light emitting source's spectrum from 380 and 100 nm wavelength (ultraviolet radiation). Nevertheless, photodegradation processes[27] also involve visible light and sometimes infrared radiation (IR). Ultraviolet radiation is the central course that creates structural damage in these processes, while light is responsible for most visible changes. These visible changes affect foremost colourants. [28] Light sensitive colourants may even fade when the ultraviolet radiation emittance of a light source is blocked.[29] This means that the part of a source's spectrum from 400 and 700 nm wavelength (visible light) is causing the fading of these colourants.[30]

Thus, R. Druzik and S. Michalski have used two methods to classify museum objects' vulnerability to light-induced damage. [31]

Primarily, the objects can be classified in five categories depending on the sensitivity of the materials, they are composed of, to ultraviolet radiation. To protect objects made of the materials that are described as sensitive to ultraviolet radiation, blocking all UV-radiation, and following the exposure guidelines may be sufficient.[32] The approximate exposure time (in case of illumination with unfiltered or filtered sunlight) that is needed to cause damage to the objects in these five categories is described in the guidelines document.

[26] Saunders, *Museum Lighting*, 125.

[27] = degradation induced by exposure to a light source.

[28] Druzik and Michalski, *Guidelines*, 42.

[29] See chapter 3.

[30] Colourant is an umbrella term for substances that can change the colour of other materials. Pigments and dyes are colourants. (11) Pigments (particle size > 0,1 µm) are colouring powders that are insoluble in the binder of a paint and form a suspension with it. (12) Dyes (particle size < 0,001 µm) are insoluble in the binder. They are bound to absorbent materials through chemical and physical forces. Lake pigments are pigments that are made of dyes absorbed by a white, unsolvable substrates (Hermann Kühn, 'Fabmaterialien, Pigments Und Bindemittel', in *Reclams Handbuchder Künstlerischen Techniken.Farbmittel,Buchmalerei, Tafel- Und Leinwandmalerei*, 2nd ed., vol. 1 (Stuttgart: Reclam, 1988), 11–12).

[31] Druzik and Michalski, *Guidelines*, 43.

[32] Druzik and Michalski, *Guidelines*,41–43.

Secondly, it was stated that light-sensitive materials can photo-deteriorate when all UV-radiation is blocked out. It was proven that visible light can cause the fading of such light-sensitive materials. Thus, R. Druzik and S. Michalski have classified their sensitivity to visible light.[33]

1.3.1. Sensitivity of materials to ultraviolet radiation

No sensitivity: inorganic materials as stone, ceramics, glass, metals.[34]

Low sensitivity (daylight through window glass (UV= 400-500 µW/lm) exposure-time to cause damage = approximately 10 years[35]): Rubbers; if they contain UV-stabilisers: paints for outdoor purposes, certain synthetic polymers and coatings.[36]

Medium sensitivity (daylight through window glass (UV= 400-500 µW/lm) exposure-time to cause damage = approximately 3 years): most types of wood, resins, varnishes (without UV-stabiliser), rubber, most indoor and artists' paints (without UV-stabiliser), ivory, bone.[37] Certain synthetic polymers (without UV-stabiliser), wool, cotton, silk, paper.[38]

High sensitivity (daylight through window glass (UV= 400-500 µW/lm) exposure-time to cause damage = approximately 2 months): wool, cotton, silk, paper (when coloured with photosensitising[39] dyes or pigments), oil paint containing photosensitising pigments, pale wood.[40]

Very high sensitivity (daylight through window glass (UV= 400-500 µW/lm) exposure-time to cause damage = approximately 1 month): low quality papers.[41]

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33 Druzik and Michalski, *Guidelines*, 43.

34 Druzik and Michalski, *Guidelines*, 43.

35 „The time estimates given are uncertain extrapolations from the full daylight spectrum estimates (…and) based on available damage spectra. The numbers provided are cautious. (Thus, it could be that the) actual time for most material-lighting combinations may be many times longer. Exposure is assumed to be approximately 8 hours per day 3.000 hours per year." (Druzik and Michalski, *Guidelines*, 43).

36 Stefan Michalski, 'Agent of Deterioration: Light, Ultraviolet and Infrared', Government of Canada, n.d., https://www.canada.ca/en/conservation-institute/services/agents-deterioration/light.html, table 5.

37 Druzik and Michalski, *Guidelines*, 43.

38 Michalski, 'Agent of Deterioration' table 5.

39 See chapter 3.2.1.2. for a definition of photosensitisation.

40 Druzik and Michalski, *Guidelines*, 43.

41 Druzik and Michalski, *Guidelines*, 4

1.3.2. Sensitivity of materials to visible light

The fading or colour shift of certain dyes and pigment were already a long-known fact when the first investigations into their cause were undertaken. A first classification of museum objects in light sensitivity categories by Thompson from 1961[42] was further developed by Feller in 1975[43], who categorised the photochemical stability of coloured objects by correlating them with the blue wool standards.[44]

The ISO Blue Wool Standard BS1006 is an international lightfastness standard that describes the light sensitivity of materials.[45] It is a test, developed in the textile industry, to measure and calibrate the permanence of coloured materials. The blue wool standard scale consists of eight textile strips, with each previous strip being three times more light-sensitive than the following one, BWS #1 being the most sensitive and BWS #8 the least sensitive class in the scale.[46] The Blue Wool references are designed to fade in a geometric progression. Each successive reference takes twice as long to fade to the same degree as its predecessor.
The following paragraph points out the differences in light sensitivity between the most sensitive and least sensitive BWS class[47]:
ISO BWS #1 classified objects can be exposed to 0.22 Mlx h[48] before showing "just noticeable fade".
ISO BWS #8 classified objects can be exposed to 120 Mlx h before showing "just noticeable fade").[49]

42 Thompson, Gerry, *The Museum Environment*, 2nd edition, Butterworth-Heinemann Series in Conservation and Museology (Sutton: Butterworth-Heinemann Ltd., 1986), 23.
43 Robert Feller, 'Studies on Photochemical Deterioration', in *Preprints* (ICOM Committee for Conservation 4th Tri-
ennial Conference Venice, Paris: International Council of Museums, 1975), 3–8.
44 There are two types of Blue Wool References: 'ISO' and 'AATCC', Feller correlated his categorisation to the ISO BWS. That is why the AATCC BWS will not be mentioned in this thesis.
45 Druzik and Michalski, *Guidelines*, 41.
46 Robert L. Feller, *Accelerated Aging: Photochemical and Thermal Aspects* (Los Angeles: Getty Publications, 1995), 6–7.
47 Still, the Blue Wool References are not correlated against actual daylight exposure. This is because real conditions vary. It is not just the light that needs taking into consideration, but the temperature and humidity also.
48 Mlx h = Megalux hours: The unit of the exposure = lux hour (lx h) (see definition in chapter 2.2). 1 Mlx h = 1,000,000 lx h.
49 Druzik and Michalski, *Guidelines*, 42.

This means that an object classified with BWS #8 can be exposed multiple times longer before “just noticeable fade” is visible than a BWS #1 classified object.[50]

Feller classified museum objects into three classes: A. Excellent materials have approximate equivalency of BWS #8 and #7 or higher. B. Intermediate materials are nearly equivalent to BWS #6 and #5 and #4. Finally, C. unstable or fugitive materials are correlating to BWS #3 and #2 and #1. Also, he proposed an intended useful display-lifetime for each class.[51]

Feller’s research was the basis for the CIE[52] publication of 2004[53], that has been hence adopted as international standard for the classification of light sensitivity[54] and vulnerability of museum objects. The CIE suggests four classes. This classification has then been adopted by the 2012 Guidelines of the Getty Conservation Institute and the Canadian Conservation Institute[55], which describe the sensitivity classes of coloured materials as followed:

No sensitivity: most mineral pigments as used in fresco painting, glass enamel (not enamel paints) and ceramics, certain carbon inks, many high-quality modern pigments developed for exterior use and automobiles.[56]

Low sensitivity (= ISO BWS #8 and #7): artists pigments classified as permanent, structural colours in insects (if UV is blocked), a few historic plant extracts (especially indigo on wool), vermillion, silver/ gelatine black-and-white prints on not resin-coated paper (if UV is blocked).[57] Dyes and pigments based on woad, red lead pigment and chrome yellow, prints and drawings in graphite, carbon black, charcoal and black chalk.[58]

Medium sensitivity (= ISO BWS #6 and #5 and #4): alizarin dyes and lakes, a few historic plants extracts (especially madder-type reds containing primarily alizarin, as a dye on wood or

[50] Druzik and Michalski, *Guidelines*, 43.
[51] Feller, *Accelerated Aging*, 6.
[52] CIE = Commission Internationale de l'Éclairage: https://cie.co.at/node/2/cie-s-objectives
[53] CIE (Commission Internationale de l’Éclairage), *Control of Damage to Museum Objects by Optical Radiation*.
[54] In the CIE publication the term „responsitivity ‘
[55] Druzik and Michalski, *Guidelines*, 41–43.
[56] Druzik and Michalski, *Guidelines*, 41.
[57] Druzik and Michalski, *Guidelines*, 41.
[58] Saunders, *Museum Lighting*, 108.

as lake pigment in all media) the bio-pigments of most feathers and furs, most colour photographs,[59] dyes and pigments based on buckthorn, weld, and broom; orpiment, realgar and Prussian blue, iron gall inks, photosensitive mineral specimen.[60]

High sensitivity (= ISO BWS #3 and #2 and #1): most plant dyes; most historic dyes and lake pigments as lac dye, cochineal, kermes or brazilwood; most early synthetic colours (including aniline dyes); many cheap contemporary synthetic colourants, most felt-tip pen inks and most ballpoint inks; most colour photographs with the word "colour" in their name (like Fujicolor).[61] Many bright bio-pigments in natural history specimens, chlorophyll-based colours in herbaria specimens, bio-pigments in many alcohol-preserved zoological specimens, silk, lignin-containing paper, jute, nylon.[62]

Many of the colourants named in the classification systems are and have been used worldwide. Nevertheless, it may be that colourants used in Thai art are not listed in them. Pigment analysis of the RSM collection objects would go beyond the boundaries of this master's thesis. Still, this could become a research field for Thai conservation scientists in the future.

In conclusion, there are, as outlined in this chapter, two valid classification system for the vulnerability of museum objects to light as agent of deterioration. The classification of the sensitivity of museum objects to ultraviolet radiation will be applied to detect which objects are susceptible to the filtered natural light in the RSM exhibition spaces and may therefore need to be exhibited in a display area where ultraviolet radiation is completely blocked out.

Furthermore, to prevent light damage to colourants that can even fade when all ultraviolet radiation is blocked out the classification of the sensitivity of colourants to visible light will be employed to the RSM collection.

These two classifications systems of museum objects are the basis to on which the illumination levels and annual exposure times are decided.

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[59] Druzik and Michalski, *Guidelines*, 41.
[60] Saunders, *Museum Lighting*, 108.
[61] Druzik and Michalski, *Guidelines*, 41.
[62] Saunders, *Museum Lighting*, 108.

1.4. Recommended exposure times

The following chapter gives an overview of recommended maximum illumination levels and recommended exposure times and lays out considerations for adequate application of these recommendations. How these recommendations can best be implemented in an exhibition lighting strategy plan is explained in chapter 4.2.

Guidelines on museum lighting with light-emitting diodes (LEDs) have been published in 2012 by the Getty Conservation Institute and the Canadian Conservation Institute in the framework of a joint research project.[63] These are based on the light-damage research of the past 50 years.

In 2020 Saunders has summed up the current exposure time recommendations (based par- tially on the 2012 guidelines) in his comprehensive study on light damage.[64] These are reproduced in Table 1.

Table 1: Recommended light levels and annual exposure, adopted from Saunders, Museum Lighting, p.202.

Vulnerability to light	Recommended maximum light level	Recommended Annual cumulative dose
No sensitivity	Unlimited (subject to surrounding objects)	Unlimited
Low sensitivity	200 lx	6.00.000 lx h
Medium sensitivity	50 lx	150.000 lx h
High sensitivity	50lx (but not on display continuously)	15.000 lx h

These are general recommendations. It is necessary to keep in mind that specific objects may show effects of photodegradation before the recommended annual dose is reached. Also, the needs of nearby objects must be considered.[65]

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[63] Druzik and Michalski, *Guidelines*.
[64] Saunders, *Museum Lighting*, 202.
[65] Saunders, Museum Lighting, 202.

1.5. Detection of light sensitive material groups in the RSM collection

As mentioned in chapter 1.2. the RSM collection has been classified in material categories. Based on this classification the collection's sensitivity to ultraviolet radiation was examined according to the classification system by Druzik and Michalski.[66] Unfortunately data about coatings and polychromy of the material groups was not available. Therefore, the assessment of light sensitivity of the collection was only performed using the available information. Thus, it is recommended to check each object's individual light sensitivity before displaying it in the exhibition. Composition of the object and potential coatings must be examined in detail before deciding how to illuminate it. In case of mixed media objects, the object should be classified according to its most light sensitive component.

However, the light-sensitivity of an object does not only depend on the material(s) it consists of, but also on the condition of the object. Pre-existing light damage as well as ongoing degradation and oxidation processes may accelerate the occurrence of light damage.[67]

1.5.1. Sensitivity of the RSM collection to ultraviolet radiation

The outer ring of Figure 4 shows the estimated sensitivity of the RSM collection to ultraviolet radiation.[68] It has been found that more than half of the collection (59.17%) can be classified as not light sensitive on basis of their materials (glazed ceramics, metal, stone, glass). Nevertheless, if coatings are existent on objects in this category, it is recommended that the sensitivity of the used colourant should be assessed in detail by the RSM conservation team. In most cases these objects will be classified medium sensitive.[69] Just a small percentage (0.64%) of the collection can be classified as having a low sensitivity to ultraviolet radiation. Again, if painted or coated these objects should be considered medium sensitive. Nearly a quarter of the collection (24.1%) should be considered medium sensitive to ultraviolet radiation. 3.35% are classified as highly sensitive and 12.68% as very highly sensitive to UV-radiation.

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[66] Druzik and Michalski, *Guidelines*, 43.

[67] Iris Groeneveld et al., 'Parameters That Affect the Photodegradation of Dyes and Pigments in Solution and on Substrate – An Overview', *Dyes and Pigments* 210 (1 February 2023): 10–11, https://doi.org/10.1016/j.dyepig.2022.110999.

[68] Based on data retrieved from P.Sadakorn's RSM collection analysis (Sadakorn, 'Collection Analysis', 169–72.)

[69] As mentioned in chapter 1.3, most indoor and artists' paints as well as resins are medium sensitive to ultraviolet radiation.

In the inner ring of the diagram (Fig.4) the RSM collection material groups are depicted in the sensitivity category to which they have been assigned. The legend below the diagram names all material groups in the RSM collection and the share of the collection they make up. (shares are given in percent- ages)

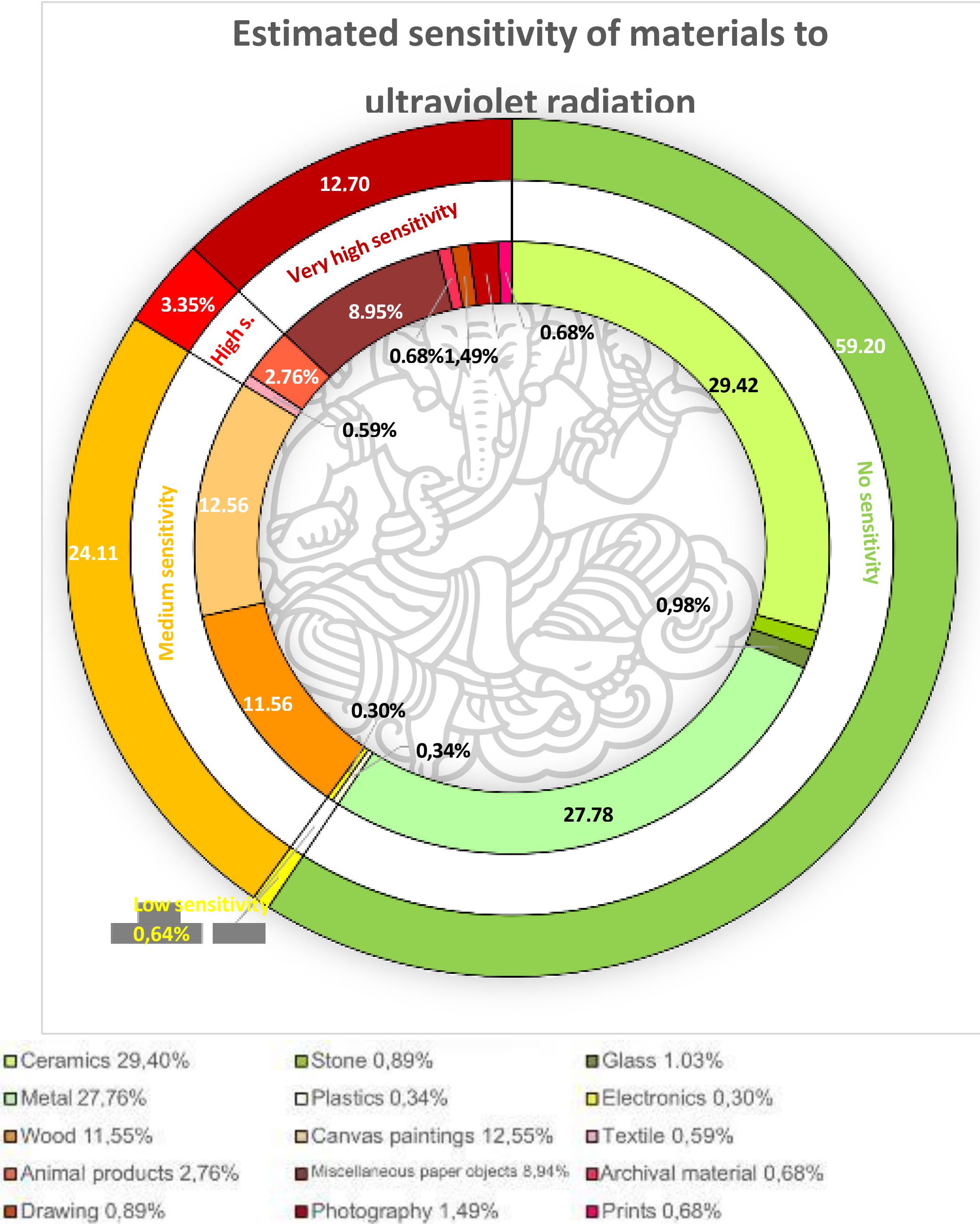

Figure 4: Estimated sensitivity of the RSM collection to ultraviolet radiation based on the collection analysis by Pornganok Sadakorn (shares in percentages).

Moreover, table 2 outlines in detail which material groups of the RSM collection have been classified by the author as not, low, medium, highly, or very highly sensitive to ultraviolet radiation on basis of the collection analysis provided by Sadakorn. The shares of these material groups in the collection are expressed as percentage.

Particularly in the group of animal products it must be considered that ivory and bone have medium sensitivity while animal hair has high sensitivity.

This approximate classification of the RSM collection's sensitivity to ultraviolet radiation may serve the conservation team, the lighting design team, and the curatorial management as decision aid for exhibition planning and lighting decisions.[70]

Moreover, entering collected information about light-sensitivity of the objects into the museum database allows groupings by sensitivity classes which can additionally assist exhibition planning.

Table 2: The sensitivity to ultraviolet radiation of the RSM collection's material groups based on data collected in the collection analysis by Pornganok Sadakorn.

Classes of sensitivity to ultraviolet radiation	**RSM collection material groups in this sensitivity category (shares in percentages)**					**Percentage of this sensitivity category in the RSM collection**
No sensitivity	Ceramics 29.4%	Stone 0.98%	Glass 1.03%	Metal 27.76%		59.17%
Low sensitivity	Plastics 0.34%	Electronics 0.30%				0.64%
Medium sensitivity	Wood 11.55%	Canvas Paintings 12.55%				24.1%
High sensitivity	Textile 0.59%	Animal products 2.76%				3.35%
Very high sensitivity	Miscellaneous paper objects 8.94%	Archival material 0.68%	Drawing 0.89%	Photo-graphy 1.49%	Prints 0.68 %	12.68%
	objects 8.94%					

[70] Nevertheless, the more data on the RSM collection's object's coatings and their composition. will be collected in the future, the more differentiated light sensitivity classification of specific object groups will be possible.

1.5.2. Sensitivity of the RSM collection to visible light

As mentioned in the previous chapter, certain colourants may fade even if all ultraviolet radiation is filtered, because visible light can induce photochemical changes in them that lead to photodegradation of their colour.[71] This makes it necessary to classify the sensitivity of colour- ants that may be most likely found in the RSM collection's material groups. Table 3 indicates the classification of light sensitivity of colourants according to the 2012 guidelines.[72] In addition, an assessment is given in the far-right column as to which groups of materials in the collection are most likely to be expected to be light-insensitive to highly sensitive colourants.[73]

[71] This photochemical change process is called photolysis. In the presence of oxygen (which is normally the case in the museum environment) photo-oxidation or photo-reduction processes take place. See chapter 3.1.

[72] Druzik and Michalski, *Guidelines*, 41.

[73] Based on data retrieved from P.Sadakorn's RSM collection analysis (Sadakorn, 'Collection Analysis', 169–72.)

Table 3 : The classification of light sensitivity of materials (adapted from Druzik and Michalski 2012) and an assess- ment in which RSM collection material groups these types of colourants may be contained

Classes of sensitivity of materials to light	Types of material	These types of materials may be contained in these RSM material groups (Modern and contemporary art- works should be classified in the category in which their most light sensitive colourant belongs)
No sensitivity (far under ISO BWS #8)	Mineral pigments as used in fresco painting, glass enamel (not enamel paints) and pigments used in the glazes of ceramics, certain carbon inks, many high-quality modern pigments developed for exterior use and automobiles.[74]	• Glazed ceramics • True glass enamel
Low sensitivity (= ISO BWS #8 and #7)	Artists pigments classified as perma- nent, structural colourants in insects (if UV is blocked), a few historic plant ex- tracts (especially indigo on wool), ver- million, silver/ gelatine black-and-white prints on not resin-coated paper (if UV is blocked).[75] Dyes and pigments based on woad, red lead pigment and chrome yellow. Prints and drawings in graphite, carbon black, charcoal, and black chalk	• Painted ceramics or metal if pigments named in the column on the left were used. • Canvas paintings containing no lake pigments and no early synthetic colours or orpiment, real- gar, and Prussian blue. • Silver/ gelatine black-and-white prints on not resin-coated paper

[74] Druzik and Michalski, *Guidelines*, 41.

[75] Druzik and Michalski, *Guidelines*, 41.

Classes of sensitivity of materials to light	Types of material	These types of materials may be contained in these RSM material groups (Modern and contemporary art-works should be classified in the category in which their most light sensitive colourant belongs)
Medium sensitivity (= ISO BWS #6 and #5 and #4)	Alizarin dyes and lakes, a few historic plants extracts (especially madder- type reds containing primarily alizarin, as a dye on wool or as lake pigment in all media) the bio-pigments of most feathers and furs, most colour photo- graphs.[76] Dyes and pigments based on buckthorn, weld, and broom; orpiment, realgar and Prussian blue, iron gall inks, photosensitive mineral specimen.[77]	• Dark pigmented feathers and furs • Thai, Chinese, or Japanese lac- quer on wood • Most colour photographs with "chrome" in their name • Drawings/ archival material containing gall inks
High sensitivity (= ISO BWS #3 and #2 and #1)	most plant dyestuff; most historic dyes and lake pigments as lac dye, cochineal, kermes or brazilwood;[78] traditional Asian organic red and yellow colourants[79]; early synthetic colours (especially aniline dyes)[80]; cheap contemporary synthetic colourants, most felttip pens inks and most ballpoint inks; most colour photographs with the word "colour" in their name (like Fujicolor).[81] Commercial printing colours, bright bio-pigments in natural history specimens, chlorophyll-based colours in herbaria specimens, bio-pigments in many alcohol-preserved zoological specimens, silk, lignin-containing paper, jute, nylon.[82]	s/ archival material con- taining en or ballpoint ink. ıs silk, jute or nylon and most iles. ıroducts containing bright d feathers and furs. hotographs with the word in their name • Prints

[76] Druzik and Michalski, *Guidelines*, 41.

[77] Saunders, *Museum Lighting*, 108.

[78] Druzik and Michalski, *Guidelines*, 41.

[79] Mostly Japanese dyes were evaluated in this study: Mie Ishii et al., 'Color Degradation of Textile with Natural Dyes and of Blue Scale Standards Exposed to White LED Lamps: Evaluation of White LED Lamps for Effectiveness of Museum Lighting', *Journal of Light & Visual Environment* 32, no. 4 (2008): 372–75, https://doi.org/10.2150/jlve.32.370.

[80] From the middle of the 19th century onwards synthetically produced organic dyestuffs and pigments became available. Early modern pigments (like for instance geranium lake pigments or azo pigmens) tend to change ap pearance (darkening, fading or colour shift) when exposed to light. (Nicholas Eastaugh et al., *Pigment Compendium: A Dictionary and Optical Microscopy of Historical Pigments* (Amsterdam: Butterworth-Heinemann Ltd., 2008), 72).

[81] Druzik and Michalski, *Guidelines*, 41.

[82] Saunders, *Museum Lighting*, 108.

In conclusion, Table 2 and table 3 showed that than half of the RSM collection seems to be insensitive to ultraviolet radiation and visible light (glazed ceramics, true glass enamel, uncoloured glass, unpainted metal and unpainted stone as well as modern and contemporary artworks containing modern pigments developed for exterior use and automobiles).

Only a small share of the collection is classified as having low sensitivity to ultraviolet radiation and light (unpainted plastics and electronics) Painted plastics can be considered also sensitive to light, depending on the colourants they contain.

About a quarter of the RSM collection is medium sensitive to ultraviolet radiation. Wood and canvas paintings fall in this category. In which sensitivity class to visible light these materials are assigned (additionally to their sensitivity to ultraviolet radiation) depends on the colourants that they may contain. To give an example, both of these material groups are considered low sensitive to chemical changes induced by visible light if their paint layers contain artists pigments classified as 'permanent'. If instead their paint layers contain early synthetic pigments or orpiment, which are classified as medium sensitive to visible light, canvas paintings and painted wood are regarded as medium sensitive to visible light. Finally, if their paint layers should contain cheap contemporary synthetic colourants or lake pigments painted wood and canvas paintings are considered highly sensitive to visible light (see table 3).

Further, only around 3% of the RSM collection are highly sensitive to ultraviolet radiation (textiles and animal products). Additionally, animal products containing feathers and furs may be considered medium or highly sensitive to visible light, depending on the bio-pigments that they contain. Moreover, textiles are also classified as highly vulnerable to visible light-induced damage.

Paper has been classified by R. Druzik and S. Michalski in the 2012 guidelines as highly or even very highly sensitive to ultraviolet radiation depending on its quality. As the composition of the papers was not analysed, all archival materials and drawings were classified as very highly sensitive to visible light as a precautionary measure. Nearly an eighth of the collection is thus acknowledged as very highly sensitive to ultraviolet radiation (miscellaneous paper objects, archival material, drawings, photography, prints.

Further, about the sensitivity to visible light of this eight of the RSM collection the following can be assumed: photographs are considered low sensitive if they are silver/gelatine black-and-white prints on not resin-coated paper, medium sensitive if they are colour photographs with the word “chrome” in their name and highly sensitive if they are colour photographs with the word “colour” in their name. Finally, drawings, prints and archival material should be classified as sensitive to light-induced damage depending on the light sensitivity of the drawing medium that was used. According to I. Groeneveld also artworks containing newly developed synthetic dyes (used for instance in contemporary artworks) should be considered highly sensitive to light, because their aging behaver has not yet been thoroughly studied.[83]

2. Scientific foundations

Light is crucial for the visibility and presentation of museum objects. Without light we cannot see the exhibited artworks. On the other hand, light – being a form of energy – can cause photochemical changes in objects that absorb[84] it. Therefore, to comprehend the development of light-induced harm in museum artifacts sensitive to light, it is crucial to be acquainted with fundamental knowledge describing the properties of electromagnetic radiation.[85]

In addition to the already motioned 2012 guidelines[86], in recent years relevant research projects were carried out by German National Museum in Nuremberg[87] and the Institute of Applied Science and Technology, National Taiwan University of Science and Technology. [88] Moreover, a recently published paper by researchers of Amsterdam Institute for Molecular and Life Sciences and Amsterdam School for Heritage, Memory and Material Culture of the University of Amsterdam gives a well-structured overview of the parameters that affect the photodegradation of dyes and pigments in solution and on substrate.[89] The findings of this research projects on lighting and light damage are presented in this chapter and chapter 3.

[83] Groeneveld et al., ‘Parameters That Affect the Photodegradation of Dyes and Pigments in Solution and on Substrate – An Overview’, 10.

[84] Franz Mairinger, *Strahlenuntersuchung an Kunstwerken* (Leipzig: Seemann-Verlag, 2003), 28.

[85] Groeneveld et al., ‘Parameters’, 1–2.

[86] Druzik and Michalski, *Guidelines.*

[87] Germanisches Nationalmuseum, ‘Entwicklung einer ökonomisch-okologischen Ausstellungsbeleuchtung | GERMANISCHES NATIONALMUSEUM’, accessed February 11, 2023, https://www.gnm.de/forschung/archiv/wege-in- die-moderne/entwicklung-einer-%20oekonomisch-okologischen-ausstellungsbeleuchtung/.

[88] H-W Luo et al., ‘Museum Lighting with LEDs: Evaluation of Lighting Damage to Contemporary Photographic Materials’, *Lighting Research & Technology* 51, no. 3 (May 2019): 417–31, https://doi.org/10.1177/1477153518764538.

[89] Groeneveld et al., ‘Parameters’.

2.1. Physical principles

Light is an electromagnetic radiation, a form of energy.[90] Light travels as waves consisting of electric and magnetic components which oscillate at right angles to the direction of propagation (Fig. 7). Electromagnetic waves are always emitted from a source, propagate through space, and carry momentum as well as electromagnetic radiant energy (Fig. 8).[91]

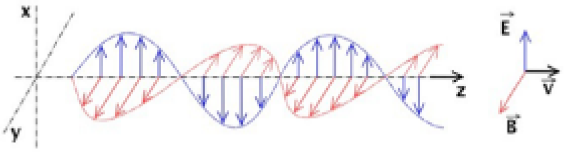

Figure 5: A linearly polarised electromagnetic wave going in the z-axis, with E denoting the electric field and perpendicular B denoting magnetic field

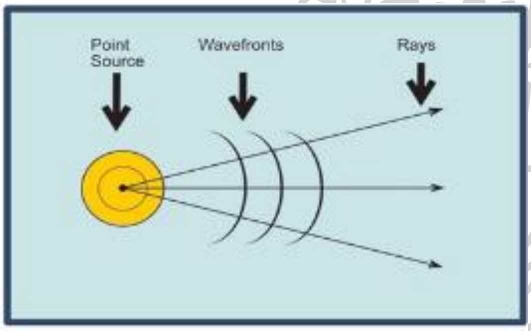

Figure 6: Emittance of light rays from a point source.

Electromagnetic radiation, such as visible light and ultraviolet radiation, has properties of waves and particles. Saunders states that "at the present time photons are seen as exhibiting properties of both waves and particles, a paradox known as wave-particle duality."[92] The properties of both classical waves and classical particles must be therefore attributed to light.[93]

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[90] Mairinger, *Strahlenuntersuchung an Kunstwerken*, 23.

[91] Luo et al., 'Museum Lighting with LEDs', 418–19.

[92] Saunders, *Museum Lighting*, 20.

[93] The properties of light as electromagnetic radiation were defined in the 19th century by James Clerk Maxwell in the Maxwell's equations (Ming-Seng Kao and Chieh-Fu Chang, *Understanding Electromagnetic Waves* (Cham: Springer Nature, 2020), 1–50). Certain properties of light could not be explained by the Maxwell's equations. Albert Einstein managed to fill in the missing information by proving that the energy delivered by light must be divided into quantized units (= photoelectric effect). These units later received the name photons (see Saunders, *Museum Lighting*, 19–20).

The energy of a photon depends on the wavelengths. Photons of visible light show high enough energy to cause photochemical deterioration. “As the wavelength of radiation gets shorter and shorter, through the blue and violet region of the spectrum of visible and into the ultraviolet, the photons possess an increasing amount of energy and are capable of inducing significant photochemical changes”.[94]

Wavelength

The term wavelength (symbol λ) describes the distance between two successive wave crests of a wave.

The unit for the wavelength is metre. Due to the very small distances between the crests, in the case of electromagnetic waves the unit nanometre (nm = 10^{-9}m) is used. Figure 6 shows a simplified depiction of three different wavelengths.[95]

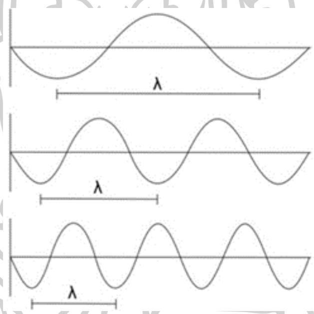

Figure 7: Three different wavelengths.

Frequency

The frequency (symbol □) of an electromagnetic wave means the number of oscillations per unit of time.

Wavelength and frequency are inversely proportional: if one increases the other decreases. The SI unit of frequency is Hertz (Hz).[96] Light waves move with a constant speed through the air – the speed of light (symbol c).[97] Its unit is m/s.[98] Frequency is speed of light divided by wavelength:

$$\nu = c/\lambda$$

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[94] Feller, *Accelerated Aging*, 45.

[95] Saunders, *Museum Lighting*, 16–17.

[96] Saunders, *Museum Lighting*, 17.

[97] The speed of light in air is approx. 300.000 km/s. (Erlach, Rudolf and Institute of Art and Technology of the University of Applied Arts Vienna, ‘Farbenlehre’ (Lecture notes, Vienna, n.d.), 8.

[98] Saunders, *Museum Lighting*, 17

Energy

To research light damage on museum objects it is important to understand the relation between wavelength (SI unit[99] = m), frequency (SI unit = Hz), and energy.[100] The shorter the wavelength is, the higher is the frequency and the greater is the energy. This means that ultraviolet radiation has higher energy than visible light and infrared radiation due to its shorter wavelength.[101] The relation between energy, frequency and wavelength is expressed by the following equations:

$$E = h\nu$$

$$E = hc/\lambda$$

E is the energy of a photon. The letter h stands for the Planck's constant (=6.62607015 × 10^{-34} m^2 kg / s). A photon's energy equals its frequency (v) multiplied by the Planck constant.[102]

2.1.1. The electromagnetic spectrum

The term electromagnetic spectrum refers to the spectrum of electromagnetic radiation, ranging over a domain of frequencies and their respective wavelengths as well as photon energies. The electromagnetic spectrum describes the relation between electromagnetic radiation of different wavelengths and frequencies.[103]

[99] SI unit= The International System of Units (SI) is the modern form of the metric system, and it is the world's most widely used system of measurement. It consists of a set of base units and derived units, with precise definitions for each unit based on fundamental constants of nature. The International System of Units (SI) is a coherent and internationally recognized system of units that is founded on seven base units. These base units are defined using specific constants of nature, making them consistent and invariant over time. The SI system provides a precise and standardized means of measuring physical quantities, facilitating international scientific communication and ensuring the accuracy and reproducibility of measurements in various fields of science and technology (Saunders, *Museum Lighting*, 18).

[100] Saunders, *Museum Lighting*, 18.

[101] Saunders, *Museum Lighting*, 18–19.

[102] Saunders, *Museum Lighting*, 18–19.

[103] Erlach, and Institute of Art and Technology of the University of Applied Arts Vienna, 'Farbenlehre', 9–10.

2.1.1.1. Properties of different wave components in the electromagnetic spectrum

The position of an electromagnetic wave within the electromagnetic spectrum can be characterised by either its frequency of oscillation or its wavelength (Fig. 9).

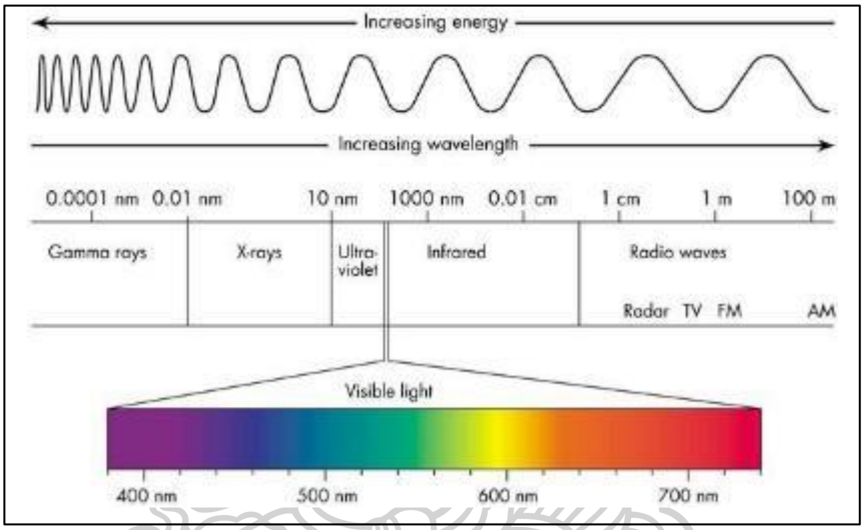

Figure 8: The electromagnetic spectrum.

In order of increasing frequency and decreasing wavelength these components of the electro-magnetic spectrum are radio waves, microwaves, infrared radiation, (visible) light, ultraviolet radiation, X-rays, and gamma rays (Fig. 9).

Electromagnetic waves in the visible part of the electromagnetic spectrum are also called light rays. Figure 9 shows that the spectral range lying between 400 and 700 nm wavelength is referred to as visible light or light. The human eye sees light with a shortest wavelength of 400 nm as violet light and light with a longest wavelength of 700 nm as red light.[104]

[104] Erlach and Institute of Art and Technology of the University of Applied Arts Vienna, 9

The wavelengths shorter than the visible spectrum lying between 380 and 100 nm is called ultraviolet radiation. Due to its high frequency and short wavelength, UV-radiation has higher energy levels than visible light.[105] Consequently, UV-radiation initiates change by cracking and altering chemical bonds that can lead to the deterioration and discolouration of light-sensitive objects over time.[106]

2.1.2. Reciprocity rule

Two other effects must be kept in mind to understand light damage phenomena: the reciprocity rule and the cumulative effect of radiation.

The Reciprocity rule, also known as Bunsen-Roscoe law, describes the principle that light transmits the same both ways, be it from the source to the detector or vice versa. When source and detector are inverted, the light still propagates in the same optical path. For most optical devices, the intent is to have a light signal travel in one direction. The reflection from the target to the source is not desirable, because this would interfere with subsequent signals. Optical isolators allow signals to pass in only one direction, while the device, an optical circulator, allows light to propagate from the source to the target, but shunts any returning light to a third location.[107]

For the establishment of a light damage mitigation concept this means that the reciprocity principle states that equal light doses, whether achieved through high irradiation intensities over short durations or lower intensities for extended periods, result in similar photodegradation efficiencies.[108]

[105] Saunders, *Museum Lighting*, 111.

[106] Seiko Jose, et al., *Handbook of Museum Textiles, Volume II: Scientific and Technological Research* (Beverly: Scrivener Publishing LLC, 2023), xiii.

[107] Saunders, *Museum Lighting*, 93.

[108] Groeneveld et al., ‘Parameters’, 4.

2.1.3. Cumulative effect

Moreover, the damage caused by light to objects is cumulative.[109] Visible changes in the material will result from the cumulative effect of radiation at a certain point of time that depends on the type of object and type of radiation.[110] The effect describes the impact that the total amount of a radiation that an object is exposed to will have over a certain exposure time. The cumulative exposure is the product of the time of exposure and the light level of this exposure.[111]

During the exposure to light, photochemical and in the worst case even thermal changes (i.e., in the case of longer wavelength of radiation) to the materials, the art object is composed of, can occur.[112] Details of these deterioration processes will be explained in chapter 3.

2.2. Light sources and the emittance of light

In the following chapter the process of light emission will be explained and light sources available for museum lighting will be described with a focus on LEDs.

2.2.1. The process of light emission

Light-emitting substances emit visible light that can illuminate an object and thus make it visible for the human eye. Atoms or molecules of a light-emitting substance undergo excitation, reaching higher energy levels through supply of energy (e.g., heat, electrical discharge, electron impact, chemical energy, etc.). This excitation leads to the movement of electrons into higher orbits or the adoption of different vibrational states. As they return to their energetically favourable ground state, the previously absorbed energy is released as electromagnetic radiation, producing a characteristic line spectrum for each element. Quantum physics dictates that no two electrons in an atom may have the same energy level, and when atoms approach each other, discrete energy levels broaden into energy bands, resulting in broader emission bands.[113]

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[109] Saunders, *Museum Lighting*, 241.

[110] Saunders, *Museum Lighting*, 84.

[111] Saunders, Museum lighting, 93.

[112] Feller, *Accelerated Aging*, 143.

[113] Erlach and Institute of Art and Technology of the University of Applied Arts Vienna, ‘Farbenlehre’, 11.

Lighting technology describes the properties of light sources. The following lighting technology terms will be explained to give the foundation for the discussion of various light sources.

Luminous flux

The luminous flux (symbol $\propto$) is the total light output emitted by a light source in all directions of the room. The ratio of luminous flux to supplied electrical power indicates the luminous efficacy of a lamp. Its unit is lumen (lm).[114]

Luminous intensity

A light source generally emits its luminous flux F at different intensities in different directions. The intensity of the light emitted in a particular direction is referred to as luminous intensity (symbol I). The unit is Candela (cd).[115]

Illuminance

The illuminance (symbol E, unit: lux (lx).) indicates the ratio of the incident luminous flux to the illuminated surface. The illuminance is 1 lx if the luminous flux of 1 lm strikes an area of 1 m^2 homogeneously.[116]

Colour Temperature

The colour temperature of light refers to the temperature at which an ideal black-body radiator emits light of a similar colour to the light source in question. A black-body radiator is an object that absorbs all incoming radiation and then emits radiation over a wide range of wavelengths based on its temperature.[117]

[114] Günter Hilbert, *Sammlungsgut in Sicherheit* (Berlin: Gebr. Mann Verlag, 2002), 4–5.

[115] Erlach and Institute of Art and Technology of the University of Applied Arts Vienna, 'Farbenlehre', 15.

[116] Erlach and Institute of Art and Technology of the University of Applied Arts Vienna, 'Farbenlehre', 16.

[117] Saunders, *Museum Lighting*, 61.

Colour temperature is quantified in Kelvin (K) and is primarily used in the field of radiative physics to describe the spectral distribution of a light source's emission[118]. It is determined by examining the peak wavelength of the light source's spectral power distribution. The higher the colour temperature, the shorter is the dominant (peak) wavelength. Light with a high colour temperature appears cool and blueish, while lower colour temperatures correspond to longer wavelengths and warmer or reddish light.[119]

Spectral power distribution

The spectral power distribution (SPD) of a light source is a graphical representation of the ratio of spectral concentration at a given wavelength to the concentration of a reference wave-length.[120]

Different light sources do not emit all wavelenghts at equal lintensity. The light of five light sources with similar colour temperature may appear white, still their SPDs can differ strongly. While these five light sources have different SPDs, each of them emits light across the visible spectrum in a way that stimulates all three cone photoreceptors in the human eye to a similar extent (to see the emitted light as 'white' light).[121]

2.2.2. Light sources

In gallery lighting, natural light and various artificial light sources have been used to illuminate artworks. While in the 19th century mainly natural light and gas lamps were used, the second half of the 19th and the 20th century brought the use of various light sources in museums, such as incandescent lamps[122], tungsten halogen lamps and fluorescent lamps.[123] In the 21st century solid-state light sources, Light Emitting Diodes (LEDs) became an economically, efficient, and low-maintenance alternative (Fig. 9, 10 and 11).

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[118] Saunders, *Museum Lighting*, 188.
[119] Saunders, *Museum Lighting*, 188.
[120] Saunders, 23.
[121] Saunders, *Museum Lighting*, 2

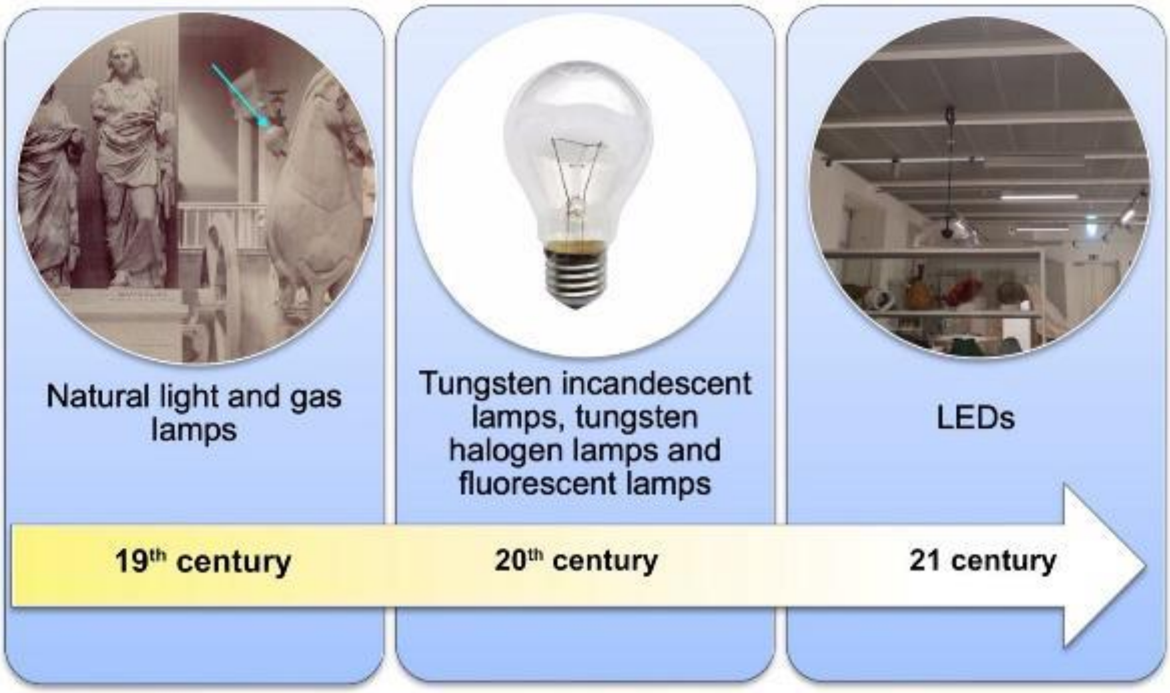

Fig. 9, Fig. 10 and Fig. 11: Timeline depicting the use of light sources in museums. From left to right:

Figure 9: The Mausoleum of Halicarnassus room in the British Museum,1920, photography,
Figure 10: A 230-volt incandescent light bulb with a medium-sized E27 (Edison 27 mm) screw base,
Figure 11: The LED lighting of the exhibition "Conservator at Work ", by Institute of Conservation, University of Applied Arts Vienna in the AIL exhibition rooms in Vienna, Austria, 2023.

Natural light sources

Natural light can vary strongly from location to location. It depends on season, weather (particularly the extent of cloud cover), and time of day. Northern hemisphere natural light contains UV-radiation with a range of 400-1600 µW/lumen (depending on time of day).[124] Daylight through window glass contains UV-radiation (with UV-A and UV-B components) with a range of 400-1600 µW/lumen, depending on time of day. Direct sunlight falling through a window on an object has an illumination level of 30.000-35.000 lx.[125]

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[122] Martina Griesser-Stermscheg, *Die Kunstgeschichte Ergänzen: Buntmetall Und Elektrische Glühbirnen. Die Kirchenausstattung Der Donaufelder Kirche Im Zeichen Des Wiener Sezessionismus* (Wien: Böhlau, 2009), 142–45.

[123] Hilbert, *Sammlungsgut in Sicherheit*, 18–36.

[124] G.Hilbert states that the northern hemisphere natural light can vary strongly depending on the season. In winter (December) outdoor daylight illumination levels of 5.900 lx at midday have been measured. At midday in summer in summer (June) 18.900 lx were measured (Hilbert, *Sammlungsgut in Sicherheit*, 15).

[125] Druzik and Michalski, *Guidelines*, 41–43.

Moreover, the spectrum of unfiltered daylight contains infrared radiation.[126] This type of radiation has lower energy than visible light. Still, it can cause damage to museum objects by heat- ing up the local environment.

Also the colour temperature[127] of natural light depends on season and daytime.[128] G.Hilbert describes the properties and the measurements of daylight at a specific location.[129] Strategies for the control of natural light will be discussed in chapter 4.1.

Artificial light sources

Artificial light sources produce light through human-made processes and are fuelled by electricity. Those of these light sources, that may be used in the museum environment, are classified into thermal light sources, gas discharge lamps and solid-state light sources.[130]

Thermal light sources

A continuous spectrum of light is produced due to the large number of atoms and molecules in a glowing solid or melt and the resulting variety of possible energy states.

Solids begin to glow at a temperature of around 500°C, and as the temperature rises, an increasing proportion of visible radiation is produced. The first visible light, that is emitted when the lamp is turned on, is red. This then changes to yellow and above 1000°C to white. As the temperature continues to rise, the colour of the light changes only slightly, but the luminosity increases. The most powerful lamps have temperatures of around 3000°C.[131]

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[126] Infrared-A radiation has a range 700 nm–1.400 nm, Infrared-B radiation of 1.400 nm–3.000 nm and Infrared-C radiation of 3.000 nm to–1 mm.

[127] For the definition of colour temperature see chapter 3.2.2.

[128] For instance norther sky daylight has a colour temperature of approximately 7.500 K, while northern sky noon sunlight has a colour temperature of 4.500 K (Saunders, *Museum Lighting*, 189).

[129] Hilbert, *Sammlungsgut in Sicherheit*, 13–17.

[130] Saunders, *Museum Lighting*, 75.

[131] Erlach and Institute of Art and Technology of the University of Applied Arts Vienna, ‘Farbenlehre’, 11

Examples of this type of light source are tungsten incandescent lamps.[132] Incandescent lamps have been a traditional and widely used type of lighting in the 20th century.[133] However, they are less energy-efficient and emit higher values of thermal radiation than gas discharge lamps and solid-state light sources.[134] Furthermore, incandescent lamps have higher UV-radiation levels (around 40-75 □W/lumen) than other artificial light sources.

Gas discharge lamps

The production of light through gas discharge relies on electrons being accelerated by an electric field.[135] This acceleration allows them to excite or ionize atoms and molecules through collisions. When these atoms return to their ground state, they emit electromagnetic radiation. The spectral distribution is influenced by the electron's spectral behaviour. By coating the glass interior with luminescent materials, the ultraviolet component transforms into visible light, and the emitted light's colour can be controlled. These light sources are more efficient as they do not rely on heating, unlike thermal radiators, resulting in less heat emission.[136]
Examples for gas discharge lamps are fluorescent lamps, compact fluorescent lamps (CFLs). and high-intensity discharge lamps (HID).

Solid-state light sources (SSL)

Solid-state lighting refers to lighting systems that use solid-state electronic devices to produce light. Inorganic light-emitting diodes[137] (LEDs) and organic light-emitting diodes (OLEDs) are solid-state light sources.[138]

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[132] Erlach and Institute of Art and Technology of the University of Applied Arts Vienna, 'Farbenlehre', 11–12.

[133] Saunders, *Museum Lighting*, 76.

[134] Hilbert, *Sammlungsgut in Sicherheit*, 23.

[135] Hilbert, *Sammlungsgut in Sicherheit*, 18.

[136] Erlach and Institute of Art and Technology of the University of Applied Arts Vienna, 'Farbenlehre', 12.

[137] A diode is a structure that brings two semiconductors in contact with each other. In the junction between these semiconductors a conduction band is established. When electricity is supplied to the diode, electrons can move in this conduction band between the semiconductors, whereby energy is set free in the form of photons of light (Druzik and Michalski, *Guidelines*, 8).

[138] Druzik and Michalski, *Guidelines*, 7.

White light can be generated by using a broadband white, fluorescent compound (e.g., a yellow phosphor disc) excited by a short-wavelength (blue or purple) light-emitting semiconductor chip (the LED). The phosphor emits light of lower energy than the exciting photons, a phenomenon called the Stokes shift. Blue or purple-pumped LEDs differ primarily in the wavelength of light they use to excite the phosphor or semiconductor material within the LED to produce visible light. Blue-pumped LED chips[139] emit light with a wavelength of 450 to 480 nm. Purple-pumped LEDs on the other hand emit light with a wavelength of 380 to 420 nm.[140]

Furthermore, LEDs are more efficient than thermal radiators because they do not depend on heat to generate light and emit little to no infrared radiation. Another benefit of solid-state light sources is their spectrum which can be adjusted during production for various applications. Available LED-products have different colour temperatures[141] and some products allow adjusting the colour temperature. They operate through electroluminescence at a lower temperature compared to incandescent sources.[142]

When choosing an artificial lighting system for a museum, light sources with high damage factors[143] should be avoided. Further, it should be aimed to block the light source's ultraviolet radiation. Finally, a light source with high luminous efficacy should be chosen to reduce CO2 emissions.

<u>Benefits and disadvantages of Solid-state light sources</u>
In the following paragraphs two frequently used artificial light sources for museums will be compared: Low-UV-fluorescent lamps and white LEDs. Low-UV-fluorescent lights emit UV-levels of around 10 to 90 µW/lumen (depending on the product type and glass used to make the lamp envelope). While the UV-levels of white LEDs lay under 10 µW/lumen,[144] they emit lower UV-levels than even the low fluorescent lamps with the smallest UV-emittance.

Saunders presents a list of damage factors for artificial light sources (the data is normalised to 1.00 for an incandescent of halogen source).[145] Low-UV-fluorescent lamps have a damage

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[139] Most blue-pumped LED chips consist of the semiconductor indium-gallium-nitride (InGaN).

[140] Druzik and Michalski, *Guidelines*, 6–8.

[141] The colour temperature of an artificial light source is measured in Kelvin (K) (Erlach, and Institute of Art and Technology of the University of Applied Arts Vienna, 'Farbenlehre', 16).

[142] Erlach, and Institute of Art and Technology of the University of Applied Arts Vienna, 'Farbenlehre', 12.

[143] Research has complimented experimentally derived relative damage factors with data derived from mathematical damage calculation (Saunders, *Museum Lighting*, 117).

[144] Saunders, *Museum Lighting*, 189.

[145] Saunders, *Museum Lighting*, 117

factor of 3.8 (or 1.2 if an UV-filter is applied that totally blocks out UV-radiation)[146] LEDs have a damage factor of 1.44 – 0,98 depending on the colour temperature.[147] This is supported by another study in which a museum fluorescent lamp caused similar degree of colour fading to natural dyes on silk as a blue-pumped white LED (BP LEDs) with approximately the same colour temperature as the fluorescent lamp. The effect of the colour temperature of a light source on its relative damage factor is explained in detail in chapter 3.2.2. Conclusivly, museum fluorescent lamps with UV-filters seem to cause the same amout of damage to light sensitive museum objects as white BP LEDs with the same colour temperature.[148]

Furthermore, recently the U.S. Department of Energy's Gateway programme has extended its support to facilitate the assessment and demonstration of high-performance solid-state lighting (SSL) products, such as LEDs. The primary goal of this evaluation was the amassment of empirical data. Also, it was aimed to foster practical expertise in the realm of advanced lighting technology.[149] The results obtained from this study consistently affirm that, among the range of LEDs under investigation, BP LEDs exhibit the least propensity for inducing material degradation.[150] BP LEDs emit lower or no ultraviolet radiation, while higher UV-values were detected in the spectral power distribution (SPD) of blue-pumped LEDs.[151]

Moreover, in times of climate change, rising energy prices and the wish of museums to behave energy efficient, an important factor for deciding on an artificial light source is the luminous efficacy (unit = lumen x W^{-1}). Low UV-fluorescent lamps have a luminous efficacy[152] of 70 to 100 lumen x W^{-1} and a European commission energy rating A, while white LEDs are more efficient (50 to 150 lumen x W^{-1} and a European commission energy rating A-A++).[153]

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[146] The values given were normalised by Saunders to 1.00 as the damage factor for an incandescent or halogen source (Saunders, *Museum Lighting*, 117).

[147] Saunders, *Museum Lighting*, 117.

[148] LED with 2869 K, Fluorescent Lamp with 3000 K.

[149] Luo et al., 'Museum Lighting with LEDs', 419.

[150] Luo et al., 'Museum Lighting with LEDs', 419.

[151] Saunders, *Museum Lighting*, 211.

[152] The luminous efficacy is the ratio of luminous flux to power (unit = lumen/ W).

[153] Saunders, *Museum Lighting*, 189.

Finally, LEDs are to be recommended as light source due to their high luminous efficacy and their beneficial influence on building cooling costs. They emit no IR-radiation and do not heat up buildings as much as other lamp types, therefore air conditioning operational costs are reduced. Using white LEDs is a way to reduce greenhouse gas emissions. It is estimated that on a worldwide share[154], museums that replaced their old lighting systems with white LEDs were able reduce their CO_2 emissions for a lamp life cycle (10 years) by 649.275.000 kg. The SO_2 emissions could also be reduced by 160.050 kg and NO_x emissions were reduced by 266.750 kg.[155]

White LEDs thus have low damage factors, best ratings of luminous efficacy and low UV-levels and seem with today's knowledge to be the safest light source for exhibition spaces. Still, LED assessment and research is still going on and since LEDs have been installed in most museums just few decades ago, the future will show if this light source type causes will be as beneficial for museum object illumination as estimated.

2.3. Measuring light

The amount of light and ultraviolet radiation emitted by sources and reaching objects can be quantified with measurement devices. There are three methods to measure light: measuring the light emitted by a source (luminous flux or intensity), quantifying the light that reaches an object (illumination), and assessing light that reaches the human eye (illuminance). Each of these measurements provides different but related information about the light's characteristics and its interaction with objects and human perception.[156]

<u>Measuring visible light</u>

In museology and conservation science the measurement of the illuminance[157] to measure visible light is the preferred method. The photopic sensitivity curve V (□□)[158] is used as the standard this measurement purpose.[159] The measurement instrument to measure visible light is called light metre. The light metre should have a photocell that is closely matched to the

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[154] R. Druzik and S. Michalski used data published by ICOM on the emission savings of 55.000 museums worldwide, that have changed their exhibition lighting to LEDs.These museum had together a life cycle CO_2 reduction of 649.275.000 kg of emission, a life cycle SO_2 reduction of 160.050 kg of emission and a life cycle NO_x reduction of 266.750 kg of emission (Druzik and Michalski, *Guidelines*, 10).

[155] Druzik and Michalski, *Guidelines*, 10.

[156] Saunders, *Museum Lighting*, 69

photopic sensitivity curve. The accuracy is given according to DIN 5032-7 respectively EN 13032-1.[160]

For most indoor applications the light metre should measure a range from 20.000 to 30.000 lx. If strong sunlight should be measured a higher sensitivity will be necessary. Modern light meters are provided with smart applications, that allow documentation and interpretation of the measured values on a tablet or smartphone.[161] An alternative to classical light meters are compact light sensors that that can be attached to the micro-USB socket of a smartphone or tablet.[162]

Measuring ultraviolet radiation

Of the three bands that ultraviolet radiation can be divided into (UV-A, UV-B and UV-C) UV-A is the most important in the museum environment. If the exhibition space has windows, a large proportion of the sun's UV-B radiation is usually filtered by window glass. A UV-meter is a instrument to measure the irradiance[163] in microwatts per lumen (µW.lumen) or watts per square metre (W.m²).[164]

The prevalent UV-metres utilized in museum settings are not calibrated to accurately measure the minimal ultraviolet radiation emitted by most LEDs. BP LEDs for museum lighting

[157] The unit of the illuminance is lux (lx) (see chapter 2.2.1.)

[158] The photopic sensitivity curve V (□), also called spectral luminous efficiency function, graphically depicts the relative contribution of different wavelengths to the brightness signal of the human eye (Saunders, *Museum Lighting*, 31).

[159] Saunders, *Museum Lighting*, 70.

[160] Beuth publishing DIN, 'DIN 5032-7:2017-02: Photometry - Part 7: Classification of Illuminance Meters and Luminance Meters', (February 2017), https://dx.doi.org/10.31030/2607119.

[161] For instance: Testo 545 - Digital lux meter with app connection (Appendix I Product data sheets)

[162] Saunders, *Museum Lighting*, 71–72.

[163] The irradiance is the radiant flux received by a surface per unit area, meaning in this context: the UV-radiation emitted by a light source that is received by an object's surface per m^2 (Saunders, *Museum Lighting*, 69).

[164] Saunders, *Museum Lighting*, 74.

purposes emit such low ultraviolet radiation values that the detection capabilities of standard UV-meters developed for the use in the museum environment are reaching their limits, when trying to detect ultraviolet radiation emitted from an SSL light source.[165]

Nevertheless, ultraviolet radiation measurements are often executed to assess if the desired UV-A threshold has been met in a certain display area. For this purpose, their sensitivity is mostly sufficient.[166]

Combined measurement instruments

There are instruments that allow the measurement of both visible light and UV-radiation. These can be useful tools to measure the illuminance in the museum environment and are often cheaper than spectral metres.[167]

Spectral metres

Spectroradiometers [168] are instruments that can measure the whole spectrum of the light incident on an object. Illuminance (lx) and irradiance (W.m²) can also be calculated by the instrument.[169]

Figure 12: Example of a combined measurement instrument

The measuring device should always have a calibration certificate in accordance with the applicable national standards.

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[165] Jim Druzik and Michalski, Stefan, 'LED Lighting in Museums and Art Galleries - Canadian Conservation Institute Technical Bulletin 36', Government of Canada, 2020, https://www.canada.ca/en/conservation-institute/services/conservation-preservation-publications/technical-bulletins/led-lighting-museums.html.

[166] Saunders, *Museum Lighting*, 74.

[167] For instance: UV Light Meter 7650 available at the Preservation Equipment Ltd, https://www.preservationequipment.com/Catalogue/Instruments/UV-Light-Monitors/UV-Light-meter. This instrument measures the illumination (Visible power range = 0.1–200.000 lx), the wavelength (visible wavelenght range= 400–700 nm), the UV wavelenght range (UV wavelength range = 300–400nm), the proportion of ultraviolet radiation present (UV proportion range = 0–10,000 µW/Lumen) and the total amount of ultraviolet radiation per square metre (UV power range = 2-50,000 mW/m²).

[168] For instance: Asensetek Spectrometer, https://www.nextgenerationled.be/EN/asensetek.html. (Appendix I Product data sheets)

[169] Saunders, *Museum Lighting*, 74.

3. Light damage phenomena

As mentioned in Chapter 2.1. photons of light can cause damage on objects that absorb them. This chapter explains the basic principles of light damage. Photochemical and thermal degradation processes will be explained. The process of dye and pigment degradation and the parameters influencing it, will be outlined.

3.1. Photochemical and thermal changes

<u>Photochemical changes</u>

Photochemical degradation of objects is irreversible and thus a serious risk factor. When photons of the emitted light reach the surface of an object, it absorbs[170] the photons which stimulate atoms and molecules of the material it is composed of. [171] If the absorbed photon's energy is greater than that of the chemical bond, the bonds can be broken (called photolytic cleavage or photodissociation).[172] This induces photochemical deterioration processes in the material structure leading to permanent structural damage. Ultimately, chain reactions occur that continue to take place even in the dark.[173]

There are different types of photochemical deterioration reactions:

1. Photolysis: is a primary reaction. This means that the energy of photons is high enough to break intermolecular bonds without a catalyst.

[170] This process is called active absorption of light.

[171] Hilbert, *Sammlungsgut in Sicherheit*, 84–85.

[172] Saunders, *Museum Lighting*, 83.

[173] Hilbert, *Sammlungsgut in Sicherheit*, 84–85.

2. Photooxidation and photoreduction: are secondary reactions. In these secondary reactions, photons cause a reaction between molecules of the object and a catalyst. For photooxidation to occur, oxygen is required to cleave intermolecular bonds. Photo-re- duction is the light-driven reduction of a substance, leading to a decrease in oxidation state.[174] These secondary reactions can be triggered by highly reactive free radicals, that are created in photolytic cleavage or by formation of an excited state of the material's molecules.[175]

The creation of free radicals is expressed in the following equation:

$$R\text{-}R' \longrightarrow R\bullet + R'\bullet$$

R and R' are representing all or a part of a molecule.
R• and R'• are free radicals (created by photolytic cleavage)

There are two types of photooxidation. The first one is a reaction between such a free radical (or a molecule excited by a photon) and atmospheric oxygen. Is described by this equation[176]:

$$R\bullet + O_2 \longrightarrow RO + O\bullet$$

The reaction between a free radical (or a molecule excited by a photon) and an oxygen-containing molecule is the second type of photooxidation.[177]

$$R\bullet + R'O \longrightarrow RO + R'\bullet$$

1. Photohydrolysis: is a secondary reaction. Photons cause a reaction between an free radical (or an excited molecule of the object) and a catalyst, in this case water. Contact of an illuminated object with water is not the only way, how reaction may occur. Water vapor[178] can also be a catalyst for photohydrolysis.[179]

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[174] Groeneveld et al., 'Parameters', 2.

[175] Saunders, *Museum Lighting*, 85.

[176] Saunders, *Museum Lighting*, 85.

[177] Saunders, *Museum Lighting*, 87.

[178] The presence of water vapor may be caused by a raise in relative humidity.

[179] Groeneveld et al., 'Parameters', 8–9

$R\bullet + H_2O \longrightarrow ROH + H\bullet$

2. Cross-linking: Natural and synthetic polymers are especially susceptible to this radia- tion-induced process because of their long chain molecules. If free radicals (or a mole- cule excited by a photon) react with other molecules of the same substance this is called cross-linking.[180]

$R\bullet + R'\bullet \longrightarrow R\text{-}R'$

Detailed descriptions of direct and indirect photochemical reactions are given by Groeneveld at al.[181] All described photochemical changes can lead to the alteration of material properties, such as stability, flexibility, solubility, or colour.[182]

Which material properties are altered depends on which spectral range (ultraviolet radiation, visible light, infrared radiation) of the emission spectrum of a light source caused the altera- tion.[183]

The spectral range lying between 380 and 100 nm (ultraviolet radiation) damages foremost the structure of materials. This can result in damage phenomena like weakening, embrittlement[184] or disintegration. Further, the exposure to ultraviolet radiation can also alter an object's appearance. Chalking, microcracking, yellowing or opacification can appear.[185]

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180 Saunders, *Museum Lighting*, 87.
181 Groeneveld et al., 'Parameters', 2–3.
182 Saunders, *Museum Lighting*, 84.
183 Saunders, *Museum Lighting*, 109.
184 Embrittlement is caused by ultraviolet radiation-induced cross-linking reactions (Saunders, *Museum Lighting*, 87).
185 Saunders, *Museum Lighting*, 109.

Changes in the appearance of an object are though most commonly caused by the spectral range lying between 400 nm–700 nm (visible light). Light alters the colour of materials. Fading and colour shifts are typical light-induced damage phenomena.[186] The caused damage de- pends on the wavelengths of emitted visible light and the colour of the illuminated object.[187] This will be explained in detail in chapter 3.2.2.

Alterations induced by the spectral range lying between 1 μm and 100 μm (infrared radiation) are thermal degradation processes and described in the following paragraphs.[188]

<u>Thermal changes</u>

Thermal degradation of materials is called thermolysis.[189] Infrared radiation (IR) that is directed on an object's surface triggers thermal changes. Thermal sensitivity is a material property that indicates whether and to what extent an illuminated material changes due to the IR-radiation it absorbs. Thermal degradation such as material failure and deformation may occur.

When photographic material is subjected to prolonged irradiation by intense light under heat development, the absorbed photon energy can lead to chemical alterations, which are manifesting themselves visually as colour fading and loss of image detail. Moreover, visual alterations due to cellulose bonds breakage may occur, ultimately impacting the visual quality and structural integrity of the photograph.[190]

Another example is the acceleration of the rate of chemical degradation of textile fibres when exposed to exceeding values of thermal radiation. Structural damage and embrittlement are the consequences.[191]

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186 Druzik and Michalski, Stefan, 'LED Lighting in Museums and Art Galleries', Fig. 5 and Fig. 6.

187 Saunders, *Museum Lighting*, 13–16.

188 Saunders, *Museum Lighting*, 88.

189 Feller, *Accelerated Aging*, 143.

190 Feller, *Accelerated Aging*, 143–51.

191 Jose, et al., *Handbook of Museum Textiles, Volume II: Scientific and Technological Research*, 7–8.

The main damage potential of artificial light sources used in museums today is that they may cause photochemical changes. Light sources used for museum illumination today, such as LEDs or fluorescent lamps, are not emitting enough thermal radiation to create thermal damage.[192]

Still, the spectral power distribution (SPD) of incandescent lamps and sunlight can contain sufficient infrared radiation to create thermolysis of a light-sensitive object's structure.[193] In lighting systems with incandescent lamps, exposure time and distance between light source and exhibited artwork are important factors to consider when trying to prevent thermal degradation.

3.1.1. Case study: Textile fibre degradation caused by illumination with natural light

Exhibition space illumination with daylight is posing an extensive risk to the exhibited objects. The synergy between visible light, ultraviolet radiation (400 – 1600 □W/lumen depending on time of day) [194] and infrared radiation emitted by the sun can lead to serious and irreversible damage of light-sensitive objects. [195]

Describing all relevant light- and UV-induced damage phenomena would go beyond the framework of this master's thesis. A comprehensive list of damage patterns of various material categories can be found in D. Saunders "Museum Lighting".[196]

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[192] Luo et al., 'Museum Lighting with LEDs', 418.

[193] Saunders, *Museum Lighting*, 287.

[194] Sunlight through a glass window still contains 400-500 µW/lm.

[195] Druzik and Michalski, *Guidelines*, 42–43.

[196] Saunders, *Museum Lighting*, 125–55.

In this chapter the light-induced degradation of silk fibres is used as an example of photodegradation of museum objects.[197] Silk-specific light induced damage phenomena are yellowing, embrittlement and in the last sequence structural damage like the formation of tears when stored or displayed incorrectly.[198]

3.1.1.1. Case study 1: Radiation induced damage of weighted silk

The summer dress of the Austrian Empress Sissi, made of weighted silk, shows how the specific composition of a highly light-sensitive textile may affect photodegradation efficiency (Fig. 14). Due to a label inside the dress, it was attributed to the Austrian Empress Elisabeth of Habsburg.[199] The aim of the owner was to display this frail exhibit. A conservation project was initiated to preserve it and prepare it for display.
The analysis and conservation were carried out by R. Dalhed at the Institute of Conservation (IoC), University of Applied Arts Vienna.[200]

Figure 13: The summer dress of the Austrian Empress Sissi, around 1900, owner: Schloß Schönbrunn Kulturund Betriebsges.m.b.H, dyed silk, wool and cotton

Technological aspects

The two-part dress of the Empress Elisabeth (top (bodice) and skirt) is made from a pink batiste[201] outer fabric with silk and lace appliqué inserts.[202]

[197] A common method to assess a textile’s condition is the measurement of the pH value is. An acidic pH value can be an indication of the advanced degradation process of the fibres or contribute to this process. Moreover, using microscopic methods, damage to the fibre surface can be detected. Further, the mechanical integrity of textile fibres can be determined by means of tensile strength tests.

[198] Caroline Dalhed, ‘Zweiteiliges Sommerkleid Der „Kaiserin Elisabeth “- Bestandsaufnahme Und Erstellung Eines Maßnahmenkonzeptes, Sowie Exemplarische Musterrestaurierung’ (Diploma thesis, University of Applied Arts Vienna, 2021), 116–17.

[199] Dalhed, 12.

[200] Dalhed, ‘Zweiteiliges Sommerkleid’, 13.

[201] The fabric is made of a fibre blend of wool and silk. Fibre analyses were carried out by Tatjana Bayerova R. Caroline S. Dalhed, Institute of Conservation (IoC), University of Applied Arts Vienna. (Dalhed, ‘Zweiteiliges Sommerkleid’, Appendix III, fibre analysis, sample G1-2 and GR 1-2).

[202] Dalhed, ‘Zweiteiliges Sommerkleid’, 38.

Two early synthetic azo dyes were used to colour the batiste: Azoflavin S (yellow) and Sorbine red BB (red).[203]

The silk appliqué inserts consist of pink taffeta (plain weave).[204] The material of the taffeta is tin-phosphate-silicon weighted silk[205] was it was dyed with the azo dye Acid Orange 7.[206]

The dress has a light-yellow silk taffeta lining (plain weave) in the top and skirt.[207] The lining of the top is made from tin-phosphate-silicon weighted silk taffeta.[208]
The top has whale-bone reinforcements.

Between the taffeta lining and the batiste outer fabric an interlayer of thin, yellow and white silk chiffon[209] has been identified.

In light of the above, it can be sumarised that the silk appliqué inserts and the lining fabric of the dress are made of weighted silk. Weighted silk was used for clothing in Europe and North America around 1900.[210] The following paragraphs explain its manufacturing process and vulnerability to radiation.

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[203] Dye analyses were carried out by Ina Vanden Berghe, Royal Institute for Cultural Heritage (KIK-IRPA), Belgium (Dalhed, 'Zweiteiliges Sommerkleid', Appendix VII, Dye analysis).

[204] Fibre analyses were carried out by Tatjana Bayerova R. Caroline S. Dalhed, Institute of Conservation (IoC), University of Applied Arts Vienna. (Dalhed, 'Zweiteiliges Sommerkleid', Appendix III, fibre analysis, sample G3-4 and GR 3-4).

[205] Tin, phosphorus, silicon and a small amount of aluminium were detected during SEM. The SEM analysis was executed by Marta Anghelone and R. Caroline S. Dalhed, Institute of Conservation (IoC), University of Applied Arts Vienna (Dalhed, 'Zweiteiliges Sommerkleid', Appendix IV, Scientific Investigations, sample 2).

[206] Dye analyses were carried out by Ina Vanden Berghe, Royal Institute for Cultural Heritage (KIK-IRPA), Belgium

(Dalhed, 'Zweiteiliges Sommerkleid', Appendix VII, Dye analysis).

[207] Fibre analyses were carried out by Tatjana Bayerova R. Caroline S. Dalhed, Institute of Conservation (IoC), University of Applied Arts Vienna. (Dalhed, 'Zweiteiliges Sommerkleid', Appendix III, fibre analysis, sample G7-8 and GR 5-6).

[208] Tin, phosphorus, silicon, natrium and a small amount of aluminium were detected during SEM analysis in the warp and weft threads. The SEM analysis was executed by Marta Anghelone and R. Caroline S. Dalhed, Institute of Conservation (IoC), University of Applied Arts Vienna.

[209] Fibre analyses were carried out by Tatjana Bayerova R. Caroline S. Dalhed, Institute of Conservation (IoC), University of Applied Arts Vienna. (Dalhed, 'Zweiteiliges Sommerkleid' Appendix III, fibre analysis, sample G13-G14).

[210] Dalhed, Dalhed, 'Zweiteiliges Sommerkleid', 107–8.

During the manufacturing process of silk fabrics, raw silk is degummed (the fibroin filaments are cleaved from the silk component sericin, also known as silk bast) in order to gain the typical lustre of the silk threads. When silk is degummed, it loses 20-30% of its weight.[211]

However, as silks were traded by weight, this meant a lower profit for the manufacturer. This problem led to the development of the silk weighting process. In this process, substances were added to the silk fibres after degumming to compensate for the weight loss.

There are two frequently used methods to increase the weight of silk. The first, the tin-phosphate method involves the soaking of the silk yarn in a tin-tetrachloride solution, which unfor- tunately reduced the lustre of silk fibres as a side effect. Then, the yarn is rinsed with water. This was followed by the soaking in a weakly alkaline sodium-phosphate-solution to regain the lustre of the yarn and to create tin-salts remaining in the yarn to increase its weight. The pro- cess leads also to a significant reduction of tensile strength of the fabric.[212]

In the second method, the tin-phosphate-silicon method, the yarn is treated in the same way as in the first method, but this is followed by soaking it in an alkali-silicates-solution.[213] Frequently, silk was bleached before it underwent the tin-phosphate-silicon method, which caused additional reduction of fibre tensile strength.[214]

Condition

Radiation-induced damage of the pink batiste outer fabric (wool-silk-blend) and the silk appliqué inserts was detected.[215] The skirt of the dress had been stored folded and had been exposed to natural light. This led to inhomogeneous distributed deterioration of the outer fabric.

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[211] Mohan Gulrajani, ‘Degumming of Silk’, *Review of Progress in Coloration and Related Topics* 22 (23 October 2008): 79, https://doi.org/10.1111/j.1478-4408.1992.tb00091.x.

[212] Agnes Tímar-Balázsy and Dinah Eastop, *Chemical Principles of Textile Conservation* (Oxford; London: Butter- worth-Heinemann, 1998), 105, https://www.taylorfrancis.com/books/mono/10.4324/9780080501048/chemical-prin- ciples-textile-conservation-agnes-timar-balazsy-dinah-eastop.

[213] Tímar-Balázsy and Eastop, *Chemical Principles*, 105.

[214] Dalhed, ‘Zweiteiliges Sommerkleid’, 112.

[215] To investigate the condition and degree of degradation, the following parameters can be analysed: pH value, morphology of the fibres and tensile strength (Dalhed, ‘Zweiteiliges Sommerkleid’, 116).

As mentioned in chapter 1.3. silk fabrics are highly sensitive to ultraviolet radiation. The process of ultraviolet radiation induced silk fibre degradation can be described as following: Silk is a proteinaceous polymer. Undyed silk absorbs little visible light and is foremost damaged by ultraviolet radiation. The energy of ultraviolet radiation is high enough to create photolytic

Figure 14: Detail of the skirt of the summer dress of the Austrian Empress Sissi: Mechanical damage of fibers damaged by exposure to ultraviolet radiation.

cleavage of the intermolecular bonds. This initial photolysis can lead then through the cre- ated free radicals[216] to secondary reactions, for instance photooxidation.[217] This process can be enhanced by unsuitable environmental conditions, such as increased relative humidity or an acidic pH value. Ultimately, the photooxidation of silk fibres leads to a reduced tensile strength of silk fibres and sub thereafter to yellowing and embrittlement of the fabric.[218] Moreover, fibers with reduced tensile strength have a higher susceptibility for the creation of tears and holes when subjected to mechanical stress (Fig. 14)

Tests with artificially aged silk samples have shown that certain types of weighted silk (especially those weighted by tin-phosphate method) are less stable when exposed to unfiltered daylight.[219] Tin-phosphate-weighted silk has been found to have a higher sensitivity to ultraviolet radiation then untreated silk. P. Garside's aging tests prove that tin-salts in the fibres of tin-phosphate-weighted silk are responsible for the higher reaction rate. Subsequently, Ultraviolet radiation-induced damage occurs faster.[220]

Tin-phosphate-silicone weighted silks in contrary, were showing a similar aging behaviour as untreated silks in aging tests.[221]

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[216] See chapter 3.1. fort he definition of free radicals.

[217] Saunders, *Museum Lighting*, 144.

[218] Tímar-Balázsy and Eastop, *Chemical Principles of Textile Conservation*, 45–51.

[219] Paul Garside, 'Understanding the Ageing Behaviour of Nineteenth and Twentieth Century Tin-weighted Silks',

Journal of the Institute of Conservation 33, no. 2 (2010): 186–88.

[220] Garside, 'Ageing Behaviour of Tin-weighted Silks', 188.

[221] Garside, 'Ageing Behaviour of Tin-weighted Silks', 186–88.

This results in the statement that the tin-phosphate method enhances the vulnerability of silk fabrics to ultraviolet radiation while tin-phosphate-silicon method does not enhance it.[222]

3.1.1.2. Case study 2: Light- and UV-radiation induced damage of partially painted textiles

This case study of the Mongolian Thangka depicting *Arhat Kālika* (Fig. 15) indicates the deterioration of an artwork containing painted and unpainted surfaces caused by exposure to natural light.

A Thangka (Tibetan: *thang ka* or *thang ga*), which means "rolled painting", is a religious Himalayan type of painting.[223] Asian thangkas are (like painted flags) a hybrid between easel paintings and textiles regarding light stability to visible light and ultraviolet radiation. Their support materials, typically dyes cotton or silk, age as such.[224] Moreover, a significant area of the fabric is shielded by paint layers (typically there is a central painting of the revered figure on a cotton fabric sewed to the framing fabrics on the sides). This mitigates radiation-induced textile degradation in the centre of the Tangka.[225]

However, these paint layers[226] share similarities with those in easel paintings, especially those bound with glue size on linen supports, known as "*tüchlein*"[227]. The paint layer of a Thangka's central painting contains frequently a lower proportion of binding medium. Further, the paint is applied thinly. This is making any fading of pigments or colour change (darkening) in the binding medium highly noticeable.[228]

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[222] Dalhed, 'Zweiteiliges Sommerkleid', 120.

[223] Gilles Béguin, *L' Art Bouddhique* (Paris: CNRS Editions, 2009), 1–5.

[224] Thangka depicting *Arhat Kālika* consist of an upper fabric and a lining fabric.
In the upper fabric, the materials used included a yellowish-green, non-degummed silk with a slight Z-twist for the warp; a light brown bast fiber without discernible twist for the weft foundation; and for the pattern weft, 0.3 mm wide silvered paper strips were processed.
The plain weave lining fabric is composed of S-twisted cotton threads in both the warp and the weft.
The support of the painting is formed by a plain weave cotton fabric. (Eva-Maria Klimpel, 'Zwei Mongolische Thangkas' (pre-diploma thesis, University of Applied Arts Vienna, 2018), 24–31).

[225] Saunders, *Museum Lighting*, 145.

[226] On the Thangka depicting *Arhat Kālika* a whithe ground layer was found on fron- and backside oft he cotton support. The water-soluble binder, was not analysed. Using X-ray fluorescence analysis, pigments such as green malachite, lead white, lead-tin yellow, and cinnabar were identified (Klimpel, 'Zwei Mongolische Thangkas', 23).

[227] Coming from the German term "*Tüchleinmalerei*", which means "painted on a fabric".

[228] Saunders, *Museum Lighting*, 145.

The characteristic darkening and physical decay of Asian silk paintings are not solely attributable to exposure to an unfiltered light source. Scrolls that have been stored rolled, thus shielded from light and ultraviolet radiation, usually show less deterioration than those displayed.

The Thangka depicting *Arhat Kālika* demonstrates how advanced silk fibre degradation through ultraviolet radiation can lead especially in scroll paintings to further deterioration processes, such as tears and holes (and Fig. 16). [229]

Figure 15 : Detail of supporting textile's upper silk fabric: Fibre degradation caused by photodegradation and mechanical damage.

Figure 16: Thangka depicting Arhat Kālika, n.d., Mongolia, supporting textile: dyed silk, raffia fibre and silver-plated paper strips, painting: glue-bound col- our on cotton.

3.2. The photodegradation of pigments and dyes

As describes in chapter 1 all organic colourants are light sensitive. Colourants are the biggest light sensitive category in most museum collections.[230] This seems to be also the case in the RSM collection. Thus, this chapter will describe the photodegradation of pigments and dyes in detail.

[229] Klimpel, 'Zwei Mongolische Thangkas', 27–30.

[230] Saunders, *Museum Lighting*, 126.

Due to the specific material composition of painted and dyed exhibits it can become necessary to execute aging test to assess the sensivity of specific object or a similarly composed object group.

The photodegradation of dyes on an individual object can be assessed by micro fading testing. Micro fading is a quick, non-destructive and object-specific method for testing light sensitivity. The device for this type of testing is called a micro fading tester (MFT)[231] (Fig. 17). It is composed of a probe containing several lenses. These lenses focus a high energy light source into a small spot (approximately 0.3 mm) of the object that should be examined to induce accelerated photochemical ageing. Colour change in the object is tracked with a spectrophotometer. The MFT can be applied directly on the art object on display.[232]

Utilising a MFT is time efficient. Moreover, its outcomes can be evaluated instantaneously. Nevertheless, there are doubts about the reliability of MFT findings because of the substantial discrepancy in light intensity levels between the MFT (the spot in the MFT illuminates the object with 5000000 lx) and the usual illumination found in galleries (less than 200 lx).[233]

Figure 17: Example of a micro fading tester (MFT)

[231] For example: Instytut Fotonowy Sp. z o.o. https://www.fotonowy.pl/products/micro-fading-tester/ This product is also available through a Taiwanese partner company (Dean Tech Co., Ltd). 1F, No. 559-1, Section 1, Wenhua 2nd

[232] Groeneveld et al., 'Parameters', 4.

[233] Groeneveld et al., 'Parameters' 4.

3.2.1. Parameters influencing the photodegradation

Photodegradation of organic colorants is influenced by both internal factors (chemical structure and concentration of the dye, used solvents and substrate in case of pigments) and external factors (the light source characteristics, the presence of oxygen, the temperature and humidity of the environment and catalysts).[234]

3.2.1.1. External factors

- Light intensities: higher light intensities increase photodegradation efficiency and reaction rates, but the relationship between light intensity and photofading is not universally consistent across different dyes.[235]

- Time: photodegradation efficiency of dyes increases with longer exposure times. How- ever, deviations from the expected reciprocity principle are noted, especially in less light-stable dyes. [236]

- Oxygen: The presence of oxygen is a parameter that catalyses photodegradation at great extent. In aerobic environments, oxygen interacts with excited dye molecules which leads to the formation of the highly reactive oxygen allotrope O_2. This oxygen allotrope enhances dye decomposition. For the majority of organic dyes, reducing the concentration of oxygen typically results in slower rates of photodegradation, but this does not lead to a complete stop of the fading process.[237]

[234] Groeneveld et al., ‘Parameters’, 3.

[235] Groeneveld et al., ‘Parameters’, 3.

[236] Groeneveld et al., ‘Parameters’, 4.

[237] Groeneveld et al., ‘Parameters’, 5.

- Temperature: It has been observed that the influence of ambient temperature has a minor effect on the photodegradation of dyes compared to other more relevant param- eters. [238] Nevertheless, the rate of chemical reactions is increased with increasing tem- perature.[239] Thus, when studying dye and pigment photodegradation it is important to keep in mind that increasing and especially fluctuating temperatures enhance fibre degradation of textiles and the deterioration of paint layers.

- Humidity: Ambient humidity levels are having a substantial impact on dye photodegra- dation processes.[240] A decrease in relative humidity has been shown to have a dual effect on the photodegradation process of dyes. Firstly, it impedes the access of moisture to the dye molecules. This lowers the rate of moisture-induced degradation. Sec- ondly, the breakdown of big dye aggregates is reached by this reduction in humidity. This disintegration potentially reduces the susceptibility of these aggregates to photolytic deterioration. [241]

Moreover, the relationship between humidity and oxygen's influence on the photodegradation of colourants is suspected to be closely intertwined. Still, as for now no studies have conclusively demonstrated that oxidative pathways are more prevalent in environments with high relative humidity.[242]

- External Photocatalysts: A photocatalyst accelerates the rate of photodegradation by creating reactive radical species on its surface. Absorbed oxygen and water molecules undergo then transformation into extremely reactive superoxide ions and hydroxyl radicals, respectively, which react with the dye molecules. This causes the decomposition of organic dyes.[243]

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[238] Groeneveld et al., ‘Parameters’,5.

[239] Saunders, Museum Lighting, 123.

[240] Saunders, 122.

[241] Groeneveld et al., ‘Parameters’, 8.

[242] Groeneveld et al., ‘Parameters’ 9.

[243] Groeneveld et al., ‘Parameters’, 6.

- Pollutants: There are two ways how the presence of pollutants may increase photo- degradation processes. Primarily, photo-oxidation may be enhanced by using high-energy artificial light sources that generate reactive pollutants. LEDs do not produce such pollutant gases but biocidal lamps in water circulation systems may do. The most common pollutants emitted by light sources are nitrogen dioxide, peroxyacetyl nitrate and ozone.[244]

Moreover, exited species can be generated by the absorption of light. These excited species may then react with ambient pollutant molecules.[245]

3.2.1.2. Internal factors

- Solution vs. substrate: Photodegradation mechanisms of colourants insolution may differ from those on substrates.[246] The colourfastness of natural organic dyes and pig- ments is heavily influenced by the nature of the mordant that is used in the dyeing of textiles and on the substrate that is used in pigment production. Equally, the extraction process of the natural organic colourant contributes to its colourfastness.[247]

- The amount of colourant used in the object: The amount of colourant used in the object affects how apparent light damage is to the viewer's eye. For instance, colour change or fading of a textile dyed with a relatively small amount of dyestuff will become notice- able earlier than colour change of a thickly applied paint layer.[248]

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[244] Saunders, *Museum Lighting*, 123.

[245] Saunders, *Museum Lighting*, 123.

[246] Groeneveld et al., 'Parameters That Affect the Photodegradation of Dyes and Pigments in Solution and on Substrate – An Overview', 7–9.

[247] Saunders, *Museum Lighting*, 128.

[248] Saunders, *Museum Lighting*, 129.

- <u>The material, that the dye is applied on:</u> Dyes with the highest sensitivity to visible light fade regardless of the material they are bound to (for example yarn). The photodegra- dation of dyes that are fewer light sensitive is though influenced by the properties of the yarn and by the mordant[249] that was used for the fixation of the colourant. Some dyes display a lower light sensitivity on wool, others on cotton. The individual combina- tion between dye, yarn and mordant define the susceptibility to fadeing.[250]

- <u>Internal Photocatalysts:</u> Pigments and coatings often contain metals that can behave as a catalyst (in the case of damage to polymers also called photosensitizers[251]) for indirect photochemical reaction. Such metals are for instance titanium dioxide, zinc ox- ide, aluminium oxide, or iron oxide.[252]

In conclusion, the intensity and time of exposure are naturally the most influencing parameters affecting the photodegradation of organic colorants, such as dyes and lake pigments. Oxygen, that is omnipresent in collections, has the second highest effect on dye photodegradation, but it cannot be blocked. Relative humidity and pollutants in the museum environment should be closely monitored and controlled. An increase in temperature affects photodegradation less than other parameters. Still, controlling the environment is had proven to be beneficial to stop dye degradation.[253]

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[249] Aluminium-based mordants lead to a higher stability of deyings than tin-based mordants do (Saunders, *Museum Lighting*, 144).

[250] Saunders, *Museum Lighting*, 144.

[251] Photosensitization is a light-induced damage process of polymers. It describes the process by which another molecule (for example zinc oxide containing white pigment) absorbs light and then causes the degradation to the nearby molecule of another substance (for example a synthetic pigment with polymeric structure or a binding me- dium) (Saunders, *Museum Lighting*, 86).

[252] Groeneveld et al., ‘Parameters’, 3.

[253] Groeneveld et al., ‘Parameters’, 3–6.

Internal factors cannot be control after the end of the manufacturing process, but it is important to consider these four findings when calculating the annual exposure dose for a specific object. A rise in dye concentration leads to reduction of photofading. Secondly, in solutions, photochemical reaction rates are typically higher than on substrates due to the enhanced mobility of dye molecules, catalysts, and oxygen. Additionally, more uniform light distribution in well-mixed solutions contributes to this increased rate. Thirdly, the solvent used in the manufacturing process and the pH level can influence the dye's chemical configuration, potentially modifying it

light sensitivity. As fourth aspect the type of substrate (for instance textile or paper) that the dye is appplied to influences photochemical reactions: proteinaceous substrates mostly lead to reduction of photodegradation processes. Non-proteinaceous substrates enhance photooxidation reactions. Finally, certain pigments, so-called photocatalysts also increase the reaction rate. [254]

3.2.2. The effects of a source's colour temperature and SPD on its relative damage factor

Another parameter influencing the photodegradation of pigments and dyes is determined by the light source itself. For museum lighting purposes LEDs with different colour temperatures and SPDs are available. This chapter will describe the relation between colour temperature, SPD[255] and relative damage factor of LEDs in detail.

Photodegradation is influenced by the light source's wavelength. Colourants, like unstable and thus highly sensitive dyes can fade by radiation of the visible part of the spectrum, while more stable colourants fade just when exposed to ultraviolet radiation. This is dependent both on their absorption spectrum and the energy level of the absorbed light.[256]

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[254] Groeneveld et al., 'Parameters', 11.

[255] For the definition of colour temperature and SPD see chapter 2.2.1.

[256] Groeneveld et al., 'Parameters', 4.

An absorbtion spectrum displays how much electromagnetic radiation is absorbed by a substance at various wavelengths. Each chemical element or compound has a unique absorption spectrum.The Grotthuss-Draper Law states that only the radiation which is absorbed by a material can cause photochemical damage.[257] This means that "the damage caused by radiation at a specific wavelength depends not only on its energy but also on whether its radiation is absorbed by the (illuminated) material," as can be traced in the absorption spectrum. Subsequently, there is a relation between the colour of a material and the probability of light-induced damage.[258] Coloured materials absorb light similar to their own colour and reflect light of an- other colour.

For instance, green and blue colourants are less affected by the blue range of a light source's spectrum, because they reflect blue light and do not absorb it. On the other hand, red and yellow colourants absorb blue light.

For a long time, light damage research was based on the hypothesis that purple and blue wavelengths (400 to 460nm) of the visible spectrum would be more damaging than higher wavelengths and that light sources with a blue peak in their spectrum would have higher relative damage factors.[259]

A study carried out by the Canadian Conservation Institute (CCI) evaluated 19 light sources (sunlight, incandescent light sources, halogen light sources, blue-pumped LEDs, and purple-pumped LEDs) based on their impact on the fading of carmine[260], a fugitive red pigment commonly used on various cultural artifacts. These light sources varied in colour temperature from 2700K to 6500K. The findings revealed that the fading of light-sensitive blue colours remained

[257] Saunders, *Museum Lighting*, 82.

[258] Saunders, *Museum Lighting*, 82.

[259] Saunders, *Museum Lighting*, 113.

[260] Highly light-sensitive carmine, often experiences fading more rapidly than other pigments, irrespective of whether it is used in oil paintings, watercolours, colour photographs, or textiles. (Druzik and Michalski, 'LED Lighting in Museums and Art Galleries').

consistent across different colour temperatures and UV-filters of light sources, while other colours examined faded. The fading rate of carmine was 50% faster for daylight at 6500 K compared to halogen at 3000 K. Conclusively, in this study it was found that the degradation of organic dyes is predominantly influenced by violet and blue wavelengths of the visible spectrum in synergy with ultraviolet radiation. [261]

This strengthens the hypothesis that blue wavelengths may have a higher damage potential than for instance red wavelengths. (Blue colours were the only ones reflecting most of the blue wavelengths. While other colours, that were absorbing blue wavelengths were showing photofading at higher colour temperatures, blue colours did not. It indicates that the photofading was caused by absorbed blue wavelengths.)

This aligns with a previous study[262], which demonstrated that an amber filter (eliminating UV, violet, and some blue light) on a daylight-simulating source could reduce the fading of natural dyes by 35%, in contrast to a 15% reduction with a UV-filter alone.[263]

Two other studies have shown that the colour temperature of a light source plays a role, but a minor one, in the creation of light damage.[264, 265] Still, they conclude that the ultraviolet range of a light source's SPD has the highest damage potential compared to the other wavelengths.

In addition, also the distribution of ultraviolet radiation of near or middle range over a light source's spectrum affects its damage potential. D. Saunders states that the damage to objects due to ultraviolet radiation increases as wavelength of the emitted radiation decreases (from UV-A to UV-B).[266]

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[261] Druzik and Michalski, 'LED Lighting in Museums and Art Galleries'.

[262] Crews, 'A Comparison of Selected UV Filtering Materials', 117-25.

[263] Patricia Cox Crews, 'A Comparison of Selected UV Filtering Materials for the Reduction of Fading', *Journal of the American Institute for Conservation* 28, no. 2 (1989): 117–25.

[264] Druzik and Michalski, 'LED Lighting in Museums and Art Galleries'.

[265] Crews, 'A Comparison of Selected UV Filtering Materials', 117-125.

[266] Saunders, *Museum Lighting*, 111

A study on the relative damage factors of three LEDs with different colour temperature came to the result that LEDs with a colour temperature of 7.000 K have a damage factor of 1.44, LEDs with 5.300 K of 1.15 and LEDs with a range of 3.400 to 3.500 K of 0.98.[267]

This was also proven by a study on LED light-induced dye degradation.[268] In this research project 22 types of natural dyes (classified from medium to highly sensitive CIE 157:2004[269]) on silk were evaluated after illumination[270] with five types of white LEDs that differed in the use of white light creation methods and colour temperature and two types of fluorescent lamps. Again, the result was that fading of the dyed silk samples decreased, if the colour temperature of the LEDs was reduced.[271]

In short, these findings can be summed up stating that the SPD of a light source has an effect its relative damage factor. Radiation emitted by a light source with a wavelength of 280–315 nm (UV-B) has the highest damage potential, followed by the spectral range of 315–380 nm. (UV-A)[272] Wavelengths between 400–460 nm (purple and blue light) have been found to be the most damaging wavelengths in the visible spectrum.

Further, a rise in colour temperature leads to a higher relative damage factor of both, LEDs and fluorescent lamps. It was found that visitors prefer higher colour temperatures in collections. Nevertheless, when displaying highly light sensitive materials, like organic colourants or feathers and furs, the increased damage factor light sources with a high colour temperature should be considered.[273]

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[267] Saunders, 117.

[268] Ishii et al., 'Evaluation of White LED', 370.

[269] CIE (Commission Internationale de l'Éclairage), *Control of Damage to Museum Objects by Optical Radiation*.

[270] The samples were illuminated first as long as the annual recommended cumulative dose suggests. (In case of highly sensitive materials this is 15.000 lx h at max. 50 lx.) Then this exposure of 15.000 lx h was repeated 10 times to see, when damage to the dyed silk samples would occur (Ishii et al., 'Evaluation of White LED', 377).

[271] Ishii et al., 'Evaluation of White LED', 377.

[272] Most artificial light sources fort he use in museums do not emit UV-C radiation (Saunders, Museum Lighting, 72).

[273] Saunders, *Museum Lighting*, 174–75.

All things considered, this means that if a light source emits ultraviolet radiation, it should be effectively filtered. Filtering blue and purple wavelength of a light source's emission spectrum should be considered when exhibiting highly light sensitive organic colourants as dyes and lake pigments.[274] Modern LEDs for museum lighting may already contain such in-built, primary filters.[275] Finally, when choosing the colour temperature of a light source factors like object visibitlity, color reproduction and preservation of objects should be taken into account.

3.2.3. Case studies: The photodegradation of pigments, dyes, and coatings

3.2.3.1. Case study 3: photodegradation of indigo on silk

Case study 3 is a presumably 18th century indigo (Poligonium tinctorium L.) dyed silk wall covering in the so-called schardroom of Loosdorf Castle, Austria (Fig. 18). It has been exposed for approximately 250 years to natural light through glass windows. The indigo dye has nearly totally faded in this period. Just after the dismantling of the wall covering for conservation, the original hue of the silk was rediscovered (Fig. 19).[276] The edges of the fabric had been shielded from light by a decorative, wooden batten. Under the batten the original hue had been preserved.[277]

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[274] Saunders, *Museum Lighting*, 214.

[275] See chapter 4.2. for details on primary filters.

[276] Zoe Ludwig, 'Die Textile Wandbespannung Des Scherbenzimmers in Schloss Loosdorf, Niederösterreich. Bestands- Und Zustandsanalyse, Maßnahmendiskurs, Sowie Restaurierung Einer Musterfläche' (diploma-thesis, Vienna, University of Applied Arts Vienna, 2024), 37–38.

[277] Personal communication with senior textile conservator Carine Gengler, IoC, University of Applied Arts Vienna on December 05, 2023.

Figure 18: Wall covering in the so-called schardroom of Loosdorf Castle, Austria, presumably first half of 18th century, dyed silk.

Figure 19: Detail of the silk wall covering: The original colour is still preserved on the edges that were covered by a wooden batten.

Environmental conditions

In the European summer, a temperature of 17 C, a relative humidity of 55% and an illuminance of 100-150 lux were measured (at midday, with half-open shutters and partial direct sunshine).[278]

Technological aspects

The quadratic schardroom in the 1st floor of Loosdorf Castle has three windows. The wall-coverings were originally present on all four walls. At the time of creation, each wall was adorned with glossy blue silk[279] fabrics displaying a white, floral pattern and framed with guilded decorative wooden battens.[280]

[278] Ludwig, 'Loosdorf', 40.

[279] Fibre analyses were carried out by Tatjana Bayerova and Zoe Ludwig, Institute of Conservation (IoC), University of Applied Arts Vienna(Ludwig, 'Loosdorf', Appendix II – Scientific research).

[280] Ludwig, 'Loosdorf', 1.

The silk fabric and the backed cotton fabric are fixed with nails on a wooden stretcher frame. This stretcher frame is anchored in the wall with masonry hooks.[281]

Condition

The room has been damaged during WW II and the wallcoverings are still in instable condition. A considerable loss of brilliance and fading of colour of the silk fabric were detected. Although several damaging factors have played a role in this deterioration process, the central agents of deterioration are presumably visible light and ultraviolet radiation.[282]

As mentioned in chapter 1.3. dyed[283] silks are not just highly sensitive to ultraviolet radiation. Further, they are also highly sensitive to visible light. The loss of indigo colour is caused by the molecular degradation reactions described in chapter 3.1. The measures illumination levels of daylight have sufficient energy to cause photolytic cleavage in the indigo molecules, which is followed by secondary reactions.

In addition, however, infrared radiation emitted by incoming sunlight it caused the wall covering to heat up. This increased the photodegradation efficiency. Moreover, an increase in temperature can cause silk fibres to expand. This increase in the volume of the fibres accelerates chemical degradation reactions and leads to a loss of stability.[284]

The damage mapping (Fig. 20) indicates that areas that were most exposed to light and ultraviolet radiation are also more susceptible to the formation of tears and holes, as the fabric structure is severely weakened here. The top third of the wall covering has the least exposure to light and therefore exhibits the most stable condition and the best condition of indigo colour.[285]

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[281] Ludwig, 'Loosdorf', 16.

[282] Foekje Boersma et al., *Unravelling Textiles., A Handbook for the Preservation of Textile Collections. London: Archetype Publications*, 2006, 23.

[283] Dyes or mordants on the other hand can act as photosensitisers to a fibre. They increase the vulnerability of silks to damage caused by visible light (Saunders, *Museum Lighting*, 144-45).

[284] Boersma et al., *Unravelling Textiles*, 50–53.

[285] Ludwig, 'Loosdorf', 39.

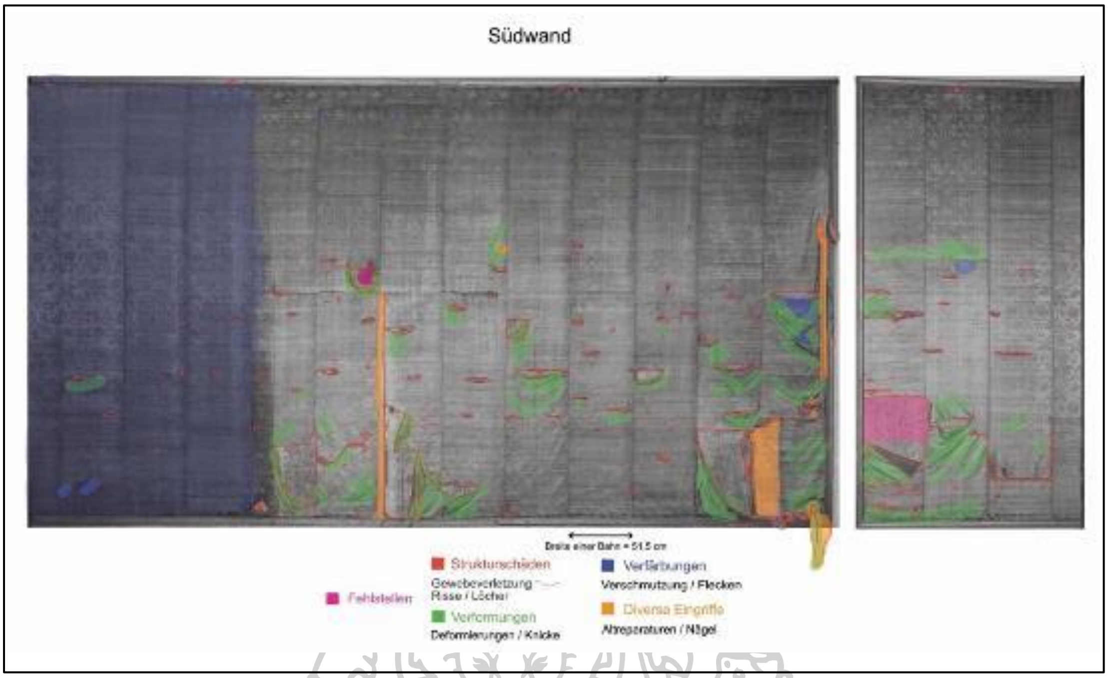

Figure 20 : Damage mapping of wallcoverings on the south wall of the schardroom by Zoe Ludwig: Structural damage (tears and holes) is marked in red.

Another reason for the low colour fastness of the fabric are the ageing properties of the natural, organic dye indigo on silk. Indigo is often described as the natural dye with the best colour fastness, but this depends on to which textile it is applied.[286] Indigo only has a low sensitivity to visible light (= ISO BWS #8 and #7) on wool[287], whereas it has a high sensitivity (= ISO BWS #3 and #2 and #1) to visible light on silk.[288] The loss of colour induced by daylight and the degradation of the silk fabric are irreversible damages.

3.2.3.2. Case study 4: fading of organic, yellow dye in a tapestry

Case study 4 is a European tapestry fragment of unknown origin and manufacturing date. Typically for tapestries that were exposed to natural light for a longer period of time the dyes on the front side have faded (Fig. 21) while the originally colour of used dyes is still visible on the back side (Fig. 22). This can be explained with the already mentioned photosensitising effect of dyes to the textile fibre. This effect enhances the fading but only on the side of the tapestry that was exposed to light.[289]

[286] Saunders, *Museum Lighting*, 144.

[287] Druzik and Michalski, *Guidelines*, 41.

[288] Ludwig, 'Loosdorf', 41.

[289] Saunders, *Museum Lighting*, 144.

Moreover, this example shows a typical aging phenomenon of tapestries. As mentioned previously, different dyestuffs have different susceptibility to visible light. Green areas are dyed with yellow organic dye and blue indigo dyestuff. Due to the fact that the photofading rate of the used yellow dye is higher than that of indigo, green areas appear now blue.[290] This can be understood when comparing the element indicated by the red arrow.[291]

Figure 21: Detail of European tapestry fragment, n.d., origin unknown, in possession of the University of Applied Arts Vienna, front: faded dyes.

Figure 22: Detail of European tapestry fragment, back: dyes are well preserved because they were not exposed to light.

3.2.3.3. Case study 5: Photofading of early synthetic dyes

The guild flag of the linen-and fustian-weavers from the Lauriacum Museum in Enns made of silk dyed with an early synthetic dye (Fig. 23) highlights that early synthetic dyes are highly light-sensitive. Exposure to unfiltered light has led to a complete fading of the violet, synthetic dye with which the entire flag was originally coloured. Photochemical reactions as described in chapter 2.1, influenced by the parameters described in chapters 3.2.1. and 3.2.2., lead to irreversible discolouration. Due to the hanging of the flag, the entire object has faded homogeneously. Only on the upper border of the flag the synthetic violet dye has been preserved because it was protected from light under the linen grommet (Fig. 24). [292]

[290] Saunders, 143.

[291] Personal communication with senior textile conservator Carine Gengler, IoC, University of Applied Arts Vienna on December 05, 2023.

[292] Pia Madlener, 'Guild Flag of the Linen- and Fustian-Weaver from the Museum Lauriacum in Enns. Technological and Condition Report, Treatment Proposal and Exemplary Restoration' (Pre-diploma thesis, University of Applied Arts Vienna, 2021), 33

Figure 23: The guild flag of the linen-and fustian- weavers from the Lauriacum Museum in Enns, 1864, dyed silk, Austria.

Figure 24: Detail of the guild flag of the linen-and fustian-weavers.

3.2.3.4. Case study 6: Photodegradation of madder lake pigment in oil bound paint layers

Figure 25: Meister von Großgmain, Pretschlaipfer triptych,1480, basswood, chalk ground, tempera, owner: Belvedere Museum, Austria: weekday side (= outer side) of the left side wing, before conservation.

The Pretschlaipfer triptych[293] (Fig. 25) was created by the European, medieval artist Meister von Großgmain in 1480. It is owned by and displayed in the Belvedere Museum, Vienna, Austria.[294]

<u>Technological aspects:</u>
Analysis of the triptych revealed that the support is made of basswood panels. Chalk ground, tempera,

<u>Condition:</u>
The madder lake containing tempera glaze on the incarnate of the depicted figures has been degraded by exposure to light. The appearance of the incarnate has changed due to the faded madder lake-containing glaze at the surface (Fig. 26). Glazes containing red lakes – like redwood, carmine, or madder lake – can

[293] In the context of Catholic art, a triptych is a three-paneled work of art, typically an altarpiece, where the central panel is flanked by two smaller side panels.

[294] Sheyda Nikjou, 'The Pretschlaipfer Triptych by the Österreichische Galerie Belvedere. Examination, Conservation and Restoration of the Inner Weekday Sides.' (diploma-thesis, Vienna, University of Applied Arts Vienna, n.d.), 1.

be discoloured or bleached by exceeding light exposure as was described in the CCI study results described in chapter 3.2.2.[295]

The cross-section of a sample taken from the incarnate area of the triptych confirms the photodegradation of the glaze: the discoloured madder lake pigments are indicated by white arrows (Fig. 27).

Figure 26: Pretschlaipfer triptych, weekday side of the left side wing: Detail of the in- carnate of the angel of the annunciation: changed appearance. due to faded madder lake-containing glaze at the surface.

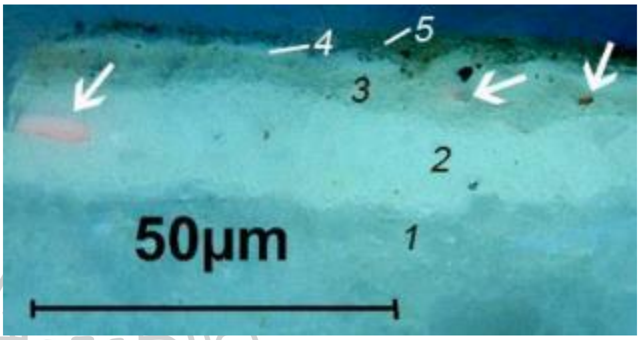

Figure 28 : Sample taken from the Pretschlaipfer triptych (outside of the left side wing, incarnate of the angel of the Annunciation, neck): cross-section, reflected-light image, UV-light, 50x: Discoloured red lake pigments indicated by white arrows.

Figure 27: Detail of baroque cabinet, n.d., oil on wood, Discolouration of madder lake: The madder lake colour layer under the metal fitting has been preserved as it was protected from light. The surrounding surface has been discoloured.

Figure 24, a detail photograph of a baroque cabinet, demonstrates the original hue of madder lake pigment in an oil bound paint layer (Fig. 28). The madder lake glaze on the cabinet's front side has faded due to exposure to sunlight (without UV-filter). Only under the metal fitting the original colour of the madder lake glaze has been preserved, because it has been shielded from light. protected from light

[295] Druzik and Michalski, *Guidelines*, 41.

Case Study 7: photodegradation of a shellac varnish on an easel painting

Case study 9, a canvas painting from Ludwig Ferdinand Schnorr von Carolsfeld depicting the last supper, demonstrates the photodegradation of a natural resin varnish (shellac).

Figure 29: Ludwig Ferdinand Schnorr von Carolsfeld, Das letzte Abendmahl, 1823, oil on canvas, in private owner- ship, before conservation.

Protective varnishes are applied to shield paint layers from the harmful effects of radiation.

When varnish and coatings are exposed to exceeding levels of light and UV-radiation their appearance changes depending on the materials they are composed of. Frequently observed changes are yellowing, darkening, or turning greyish. The speed and intensity of yellowing also depends on the quality of the coating components used.[296]

As mentioned previously, only absorbed light can cause damage (Grotthuss-Draper law) and coloured materials absorb light similar to their own colour and reflect light of another colour. This implies that transparent (=colourless) materials do not absorb radiation of the visible part of the spectrum.[297] Instead, they absorb parts of the spectrum that are invisible to the human eye, meaning ultraviolet radiation.

Radiation induced changes – like the reduction of solubility, the alteration of colour and of transparency are caused by cross-linking reactions. In these reactions a free radical (created by scission of molecule bonds by the energy of a photon) and a long-chain molecule of the varnish combine to form a larger molecule.[298] The more such cross-linking reactions take place between the long-chain molecules of the varnish, the higher is the reduction of solubility.

Unaged natural resins have a low absorption rate for visible light but are susceptible to ultraviolet radiation. This exposure can initiate the creation of chromophores, leading to potential yellowing, or it might cause oxidation reactions that change the solubility of the resin, which could make it irresolvable. [299] This should be avoided, because an irresolvable yellow varnish would lead to a permanent alteration of the original colours of the objects.

[296] Saunders, *Museum Lighting*, 152–53.

[297] Saunders, *Museum Lighting*, 82.

[298] Saunders, *Museum Lighting*, 87

The partially applied, oxidated shellac varnish on the left area of the paintings surface has changed in appearance and soloubility. Its yellowed appearance impairs the visibility of the depiction (Fig. 30).

Figure 30: Das letzte Abendmahl, Detail of : photodegraded shellac varnish (yellowed), partially over- painted.

In conclusion, the case studies have demonstrated that dyes, pigments, and coatings may be irreversibly damage when exposed to exceeding light, UV-radiation, and IR-radiation values. Thus, collection should implement light damage mitigation concepts as will be described in chapter 4.

3.2.4. Calculation of the colour damage degree of pigments

If the exact colour damage degree[300] of a pigment should be determined a 2021 established, mathematical model of pigment colour damage calculation may be used.[301]
The calculation of the colour damage degree is explained in the following paragraphs.[302]

$$D_n = \int_{380}^{780} S(\lambda) \cdot f_n(\lambda, Q)\, d\lambda$$

Dn (Colour Damage Degree): D_n is the colour damage degree of a certain pigment.

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[299] Saunders, *Museum Lighting*, 153.

[300] The colour damage degree of a pigment is the the mathematical expression of the complex photochemical damage that occurs when the pigment absorbs light. (Rui Dang et al., ‘The Mathematical Expression of Damage Law of Museum Lighting on Dyed Artworks’, *Scientific Reports* 11, no. 1 (May 26, 2021): 5, https://doi.org/10.1038/s41598-021-90520-z.)

[301] R. Dang et al. have proposed a mathematical model for calculation of the colour damage degree. Because every pigment absorbs or reflects light differently depending on its chemical structure, it is necessary to calculate the damage degree of each pigment individually by putting the light source’s SPD and the exposure time in the equation. (Dang et al., ‘The Mathematical Expression of Damage Law’, 5.)

[302] Madlener, ‘Guild Flag of the Linen- and Fustian-Weaver from the Museum Lauriacum in Enns. Technological and Condition Report, Treatment Proposal and Exemplary Restoration’, 33.

$S(\lambda)$ (Relative SPD): $S(\lambda)$ is the relative SPD of the irradiation light source, which can be measured by the spectrometer.

Q (Exposure): is the amount of exposure, which can be arbitrarily assigned. The unit of Q is Watt hour per square meter (Wh/m^2).

fn (λ, Q) (Relative Responsivity Function): is the relative responsivity function of a certain pigment to exposure and SPD, $n = 1 \sim 23$, representing $1 \sim 23$ kinds of pigments.[303]

When the light source SPD and exposure *Q* are input, the colour damage value of a specific pigment can be obtained.[304] This mathematical method can be applied to evaluate the light sensitivity of pigments and compare them with each other which can be an additional aid in the creation of a light plan[305].

[303] Dang et al., 'The Mathematical Expression of Damage Law', 5.

[304] Dang et al., 'The Mathematical Expression of Damage Law', 5.

[305] See chapter 4.2. for detailed information on light plans.

4. Decision making: Considerations for a light damage mitigation concept for Ruam Samai Museum

The control of agents of deterioration foresees five steps: "avoid, block, detect, respond and recover". [306] Chapter 4 describes how parts of a light source's spectrum that are especially damaging collections (ultraviolet- and infrared radiation) may be avoided or blocked and how light damage can be detected by monitoring. If photodeterioration processes are detected on an object, the response should be a reduction of the object's yearly exposure budget[307] [308]and/or the daily exposure time.[309] Recovering a damaged object is not possible, because light-induced damage is irreversible.[310]

Thus, the avoidance and blockage of harmful radiation values is the aim when developing damage mitigation strategies for this agent of deterioration.[311]

Light and ultraviolet radiation damage mitigation comprises six general concepts that can be employed to protect the museum object (Fig. 31).

The first concept blocks radiation from entering the building. It is the installation of light protection measures outside the windows.[312]

Further, the second concept encompasses the installation of light protection at and/or inside the window.[313]

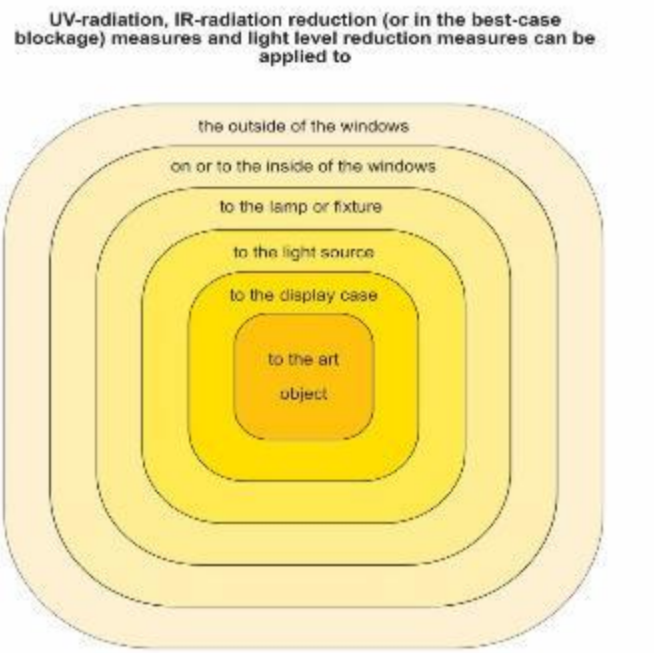

Figure 31: Schematic illustration of the six general concepts of light and ultraviolet radiation damage mitigation.

[306] Druzik and Michalski, *Guidelines*, 43.

[307] The yearly exposure budget =the amount of lux hours that a light-sensitive object may be illuminated per year.

[308] Saunders, *Museum Lighting*, 202.

[309] Saunders, *Museum Lighting*, 11.

[310] For example, faded colours of a painted object cannot be re-created (Saunders, *Museum Lighting*, 13).

[311] Druzik and Michalski, *Guidelines*, 43.

[312] Hilbert, *Sammlungsgut in Sicherheit*, 55–56.

[313] Saunders, *Museum Lighting*, 228.

Moreover, there is the option to apply ultraviolet and infrared reduction measures (or in the best-case complete blockage) on the lamp, respectively the fixture. An example for these measures is secondary filters[314].[315]

Another option (the fourth concept) is to reduce or block the ultraviolet and infrared radiation by measures that are applied on the artificial light source itself, such as primary filters[316].[317]

However, if objects are exhibited in display cases to ensure their adequate preservation conditions in the exhibition space, protective measures may be applied to the vitrine. Chapter 4.3. will introduce methods for UV- and IR-Radiation blockage by choosing appropriate glasses for the case construction.[318]

Additionally, to these five four concepts it may become necessary to protect highly light-sensitive objects in particular. In this case protective measures applied on the exhibited object itself may be considered, such as protective glazing with UV-absorbing glass.

In the following chapters the control of natural light sources in the context of museum displays will be discussed. This is followed by the introduction of methods for the control of artificial light sources. Then, the control of artificial light in display cases will be elaborated. Finally, monitoring strategies are suggested.

4.1. Control of natural light sources

Sunlight falling through a window on an object has an illumination level of 35.000 lx. Object illumination with natural light can be an option if the sunlight's ultraviolet and infrared radiation are blocked and a system for the control of illumination is applied.[319] Shutting out sunlight has another positive effect. Blocking the sun's IR-radiation can help to reduce air conditioning operational costs and thus reduce CO_2 emissions.

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[314] See chapter 4.2. for more details on secondary filters.

[315] Saunders, *Museum Lighting*, 208–9.

[316] See chapter 4.2. for more details on primary filters.

[317] Saunders, *Museum Lighting*, 208.

[318] Saunders, *Museum Lighting*, 121.

[319] Druzik and Michalski, *Guidelines*, 42.

The amount of natural light entering the exhibition rooms of a museum may change depending in time of day and (in certain climate zones) depending on the season. As mentioned, UV-emittance of the sun my vary from 400 – 1600 W/lumen, depending on the time of day .[320] This means when natural light is used for museum illumination, it should be aimed to reduce the incoming sunlight at peak times.

Light protection outside the windows:

Two methods can be applied to reduce natural light incoming through windows and thus the illuminance in the exhibition rooms:

1. Reducing the space through which daylight may enter the windows with adjustable light-impermeable elements in the form of rotating and sliding elements (either automatically or manually controlled to maintain a maximum target illuminance).[321] This system is used for example at New Tate Modern and Hamburg Art Gallery.[322] A special form of this method are automated daylight control systems for skylights.[323] These systems can direct the daylight onto certain areas of the interior and thus illuminate light- sensitive objects less strongly. Also, it is possible to direct daylight entering through the skylight to the walls. If walls are painted with titanium dioxide containing colours, this has an UV-filtering effect. Titanium dioxide selectively reflects light but absorbs UV radiation.[324] A daylight control system was installed for instance by the Bern Art Museum.[325] This method does not block UV-radiation and should thus be combined with a UV-mitigation method.

[320] Sunlight through a glass window still contains 400-500 W/lm.

[321] Automated systems use light sensors to maintain a maximum target illuminance. They should be carefully programmed to avoid a constant switching of the interior light-situation in cloudy skies (Hilbert, *Sammlungsgut in Sicherheit*, 56).

[322] Hilbert, *Sammlungsgut in Sicherheit*, 55–56.

[323] For example Arup™ custom made daylight control systems for skylights (based on adjustable lamellas and diffusion filters) as used in the the Rijksmuseum, Amsterdam, Netherlands or the V&A Medieval Renaissance Galleries, London, UK, https://www.arup.com/perspectives/publications/promotional-materials/section/rethinking-light- ing-in-museums-and-galleries.

[324] Saunders, *Museum Lighting*, 208.

[325] Hilbert, *Sammlungsgut in Sicherheit*, 58.

Figure 32: The control system consists of 7.500 elements: each element measures 700 x 700 mm and is composed of partially screen-printed textured glass on the outside structurally bonded to a folded metal tray from brushed stainless steel on the back.

Figure 33: Daylight control system designed by Arup company on the façade of the Futurium Exhibition Space in Berlin, Germany

Figure 34 : New Tate Modern in London by architects Herzog & de Meuron: construction of the daylight control systems for skylights

2. Reducing transmittance of the windows through adjustable translucent elements like diffusely scattering blinds.[326] For these UV-absorbing materials should be used. The use of light protection foils on windows is especially on historic museum buildings not recommended, because they change the external appearance of the windows and are difficult to remove.[327]

[326] Hilbert, *Sammlungsgut in Sicherheit*, 55.

[327] Johanna Runkel, 'Kunstkammer and Naturalienkabinett. The Collection of the Cistercian Abby Neukloster in Wiener Neustadt. History, Collection Items and Preservation Strategies' (PhD thesis, University of Applied Arts Vienna, 2019), 263.

<u>Light protection applied on or inside the windows</u>

1. PVB-laminated glazing: When choosing window glass for a museum country-specific regulation should be complied with.[328] Generally, a sun-protection reflective glass should be a double-pane insulating glass. Between the two panes there should be a polyvinyl butyrate (PVB) foil with a thickness of 0,76 mm. Such an PVB-foil filters most of the ultraviolet radiation contained in incoming sunlight.[329] These types of glass function as active UV absorbers for around 25 years.[330]

2. Reducing transmittance of the windows through adjustable UV-absorbing elements. These are for instance curtains, shutters or blinds that can be drawn during closing times or peak-illumination times during the day.

3. Reducing transmittance of the windows through permanently installed UV-absorbing elements. There are two ways to shield the exhibition rooms

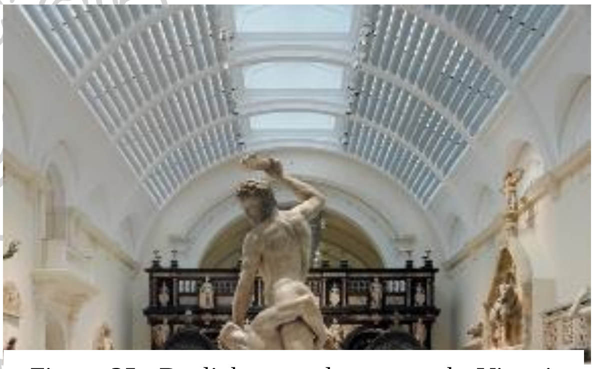

Figure 35 : Daylight control system at the Victoria & Albert Museum in London. Designed by Arup company in form of rotating and sliding elements fixed inside of the skylights.

with help of permanently installed elements at the insides of windows. Firstly, it can be decided to do without natural exhibition illumination and use an artificial light source instead. In this case the windows can be covered with darkening textiles to shut out all light. If instead natural light is desired for the illumination of the exhibition space, translucent, UV-absorbing fabrics

[328] Hilbert, *Sammlungsgut in Sicherheit*, 509.

[329] For example EVERLAM™ CLEARVIEW PVB-interlayer for double-pane insulating glass or Window Film Systems™ Solar Control UV Window Film interlayer.

[330] Saunders, *Museum Lighting*, 210.

can be mounted in front of the window (Fig. 36 and Fig. 37). For this purpose, functional fabrics should be used that filter UV- and IR-radiation. They are vapourcoated on one side with metals such as aluminium or steel and are available in various degrees of transparency.[331]

Figure 36: Jewish Museum Vienna: A UV-absorbing fabric was stretched under the parabolic glass roof and artificial light sources were installed

Figure 37 : Object depot of the Cistercian Abby Neukloster in Austria: Frame, covered with light protection fabric and inserted into the window recess.

4.2. Control of artificial light sources

To mitigate photodegradation of light sensitive museum objects caused by artificial light sources, several control strategies have been suggested.

Light plans: Light plans are generally a good method to create an overview of the lighting situation in an exhibition room. The plan should contain a floorplan of the room, light sensitive objects on display, the yearly exposure budget[332] in lux hours, the desired average illuminance for sensitive items, instructions for light- and UV control measures and potential monitoring points for regular light-and UV monitoring.[333]

Selection of Appropriate Lighting: This is a crucial aspect for light damage mitigation. Benefits and disadvantages of light sources have been compared in chapter 2.2.2.

[331] For example Company Création Baumann, silver and steel - fabrics for regulating light and warmth, product catalogue 2015, Leopold Editionen, Sitzmöbelstudio-Einrichtungen, Handelsgesellschaft m.b.H., Fiedlerstraße 2-4 4040, Austria (Runkel, 'Kunstkammer and Naturalienkabinett. The Collection of the Cistercian Abby Neukloster in Wiener Neustadt. History, Collection Items and Preservation Strategies', 263)

[332] The yearly exposure budget = the amount of lux hours that a light-sensitive object may be illuminated per year.

[333] Saunders, *Museum Lighting*, 231.

<u>Control of Light Exposure</u>: As mentioned in chapter 1 exposure recommendations for specific material categories have been developed. These recommendations give the maximal amount of lux hours (lx h) that an object should be exposed to. An exhibition lighting strategy plan includes the details of when and how the object should be illuminated and should follow exposure recommendation. The plan should involve management of intensity duration of light exposure. This can be achieved by the following measures[334]:

- The use of dimmers[335]
- Periodic lighting: The use of proximity switches, that turn on the light only when a visitor's movement is detected can help to reduce exposure times.[336]
- Shielding objects from light in specifically designed exhibition architecture like drawers or covered display cases (The cover can be removed by the visitor to regard the object)

<u>Filtering ultraviolet radiation</u>: UV filters can be applied to lamps or light sources to block ultra-violet radiation, which is as described in chapter 3, particularly damaging. The specific type of UV filter used can depend on the particular requirements of the museum or gallery, such as the sensitivity of the objects on display and the overall lighting design. The development of LED technology and UV filtering continues to evolve, offering increasingly effective solutions for protecting sensitive materials in museum environments. Saunders recommends a maximum proportion of ultraviolet of 10 μW/lm as acceptable value of filtered light sources.[337]

- Primary filters:
    1. The first type of primary filters are integrated UV-filters in the light source. Some LEDs are designed with built-in UV filters. These LEDs[338] are manufactured specifically for environments where UV exposure needs to be minimized, like museums and art galleries.[339]

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334 Saunders, *Museum Lighting*, 232.

335 Saunders, *Museum Lighting*, 229.

336 Druzik and Michalski, *Guidelines*, 43.

337 Saunders, *Museum Lighting*, 213.

338 For example ERCO™ Uniscan. https://www.erco.com/en/service/microsites/products/uniscan-a-minimalist-and- multi-talent-for-gallery-lighting-7649/.

339 Saunders, *Museum Lighting*, 208.

2. The second type of primary filters are UV-blocking Coatings. LEDs can be equipped with coatings that block UV radiation. These coatings are applied directly to the LED lens or bulb, filtering out UV rays before light is emitted by the source.[340]

- Secondary filters: In addition to built-in solutions, external UV filters can be placed over LED fixtures. These can be sheets or panels of materials that absorb or reflect UV light, and they can be added to existing lighting setups.[341]

- Diffusion filters: Diffusion filters, applied to the LED lamp spread out the light emitted by LED, which can help reducing the intensity of light emitted by the source. Diffusers can be part of an overall strategy to minimize potential UV damage.[342]

- Optical filters: These are specialized filters that can be used in conjunction with LED lighting to tailor spectral output, meaning that a desired range of wavelengths can be blocked. These can be used for instance to block the blue wavelengths when illuminating an object containing a highly light-sensitive dye.

<u>Rotation of collections on display:</u> Many art institutions have established well-developed rotation plans. Rotation plans allow limited exposure times of light-sensitive objects. When not presented in the exhibition, objects are stored in boxes or storage furniture that exclude light. Providing these ‘rest periods’ for objects in dark storage is a well-established practice to slow down light-induced deterioration, especially for organic materials.[343] Combined with regular monitoring (see chapter 4.4) this can significantly reduce the risk of photodeterioration. Moreover, incorporating rotation into exhibition design is essential for balancing public access with conservation needs.

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[340] Saunders, *Museum Lighting*, 208.

[341] Saunders, *Museum Lighting*, 208–9.

[342] Druzik and Michalski, *Guidelines*, 13.

[343] Saunders, *Museum Lighting*, 238.

Optimising viewing conditions: Lighting design and display area should be realized in a way that avoids distracting glare and reflections. Direct glare from windows or artificial light sources should be blocked. Further, reflected glare (by overhead lighting on display cases or glazed picture frames) should be reduced to a minimum extent. Moreover, strong background contrast between object and exhibition architecture should be avoided and the visual adaption of the eyes of the visitor in the transition from entrance hall to exhibition spaces should be supported.[344] Finally, a good adaptation of the visitor's eye when moving from brighter to darker museum rooms should be enabled by the lighting design.[345]

Optimising of light source properties: The optimising of the light sources colour temperature[346] and fidelity[347] can improve the visibility of the exhibited objects without increasing the light source's intensity.

[344] Druzik and Michalski, *Guidelines*, 37.

[345] Saunders, *Museum Lighting*, 279.

[346] Saunders, *Museum Lighting*, 172–76.

[347] Saunders, *Museum Lighting*, 216–19

Environmental Control: Incorrect temperature and humidity may accelerate photodegradation processes. Thus, these factors should also be regularly monitored.[348]

Use of Replicas and Digital Displays: For extremely light-sensitive items, displaying replicas (Fig. 38) or using digital displays can be an effective way to show the object without exposing the original to an artificial light source. The disadvantage of using digital displays for the presentation of digital photographs of a light-sensitive object is that the high colour temperature of computer screens may impede the visitors' colour adaptation.[349]

Figure 38 : Replicas of highly light-sensitive drawings in the exhibition 'Santini and his World of Architecture (1723-2023)' at the National Technical Museum Prague, Czech Republic.

In 'Museum Lighting: A Conservators and Curator Saunders evaluates these mentioned control strategies with regard to the risk of photodeterioration on the one hand and the visibility and access of objects to the visitors on the other hand. The elimination of ultraviolet radiation, the optimising of viewing conditions, the optimising of light source properties and the monitoring of light levels and exposure (with help of a light plan) have been found beneficial or at least neutral in both regards.[350]

4.3. Control of artificial light sources in display cases

As mentioned in chapter 3.2.1., synergies between ambient oxygen, temperature, pollutant gases and relative humidity can intensely influence light-induced photochemical reactions.[351] Generally, there are two types of vitrines, such with passive environmental control and such with active environmental control (also called microclimate cases).

[348] Saunders, *Museum Lighting*, 122–23.

[349] Saunders, *Museum Lighting*, 292.

[350] Saunders, *Museum Lighting*, 279.

[351] Saunders, *Museum Lighting*, 119.

Passively controlled showcases

Passively (environmental) controlled showcases should be firmly sealed to keep out dust and pollutants and control the amount of air that circulates through the interior.[352] The installation of lamps within display cases encountered in the past frequently criticism owing to the potential of increasing temperatures within the show case when light sources emitting thermal radiation are used. Especially incandescent light bulbs can significantly elevate the temperature within the vitrines, which may pose the risk of thermal degradation of exhibited artifacts. Furthermore, the rise of temperature in the showcase can induce perpetual convective air currents, thereby moving dust particles onto the object within. [353]

Nevertheless, due to the very low heat emissions of LEDs[354], the use of these lamps in display cases can be justified in favour of better visibility of the objects.[355]

Additionally, the use of periodic lighting (proximity switches turn on the light in the display case when visitor movement in the direct surrounding is detected) has proven to be beneficial for the preservation of highly light-sensitive objects.[356]

Microclimate cases

Microclimate cases are engineered with integrated systems to actively manage and regulate the internal environment. [357]

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[352] Barry Lord and Maria Piacente, *Manual of Museum Exhibitions* (Lanham: Rowman & Littlefield Publishers, 2014), 313.

[353] Runkel, 'Kunstkammer', 267–68.

[354] For example ERCO™ Axis showcase spotlights. These are dimmable LEDs and emit no ultraviolet radiation according to the producer. https://www.erco.com/en/service/microsites/products/axis-showcase-lighting-7851/.

[355] Runkel, 'Kunstkammer', 267–68.

[356] Saunders, *Museum Lighting*, 235.

[357] Lord and Piacente, *Manual*, 313.

A beneficial microclimate for various object and material categories has been described by Jerry Shiner.[358, 359] Studies have proven that the photo-oxidation of pigments and dyes is distinctly decelerated in a low-oxygen atmosphere.[360] Unfortunately, the maintenance of low-ox- ygen display cases is costly and difficult and thus not an applicable solution to reduce the risk of light damage.[361]

In conclusion it can be stated that freestanding cases with integral lighting hoods are probably the most common type of vitrine (wither actively or passively controlled) in museums today (Fig. 39). The light box should be separated from the display chamber (Fig. 40). The light box should have a separate access from the display chamber so that maintenance works on the lamps can be done without opening the display chamber. LEDs do not need such light boxes, because they emit no thermal radiation.[362]

In any case, the vitrine should not only create a microclimate beneficial for the object but also block UV- and IR-radiation from damaging the exhibited object (Fig. 41). Thus, a display cases' panes[363] should consist of UV-absorbing glass, meaning glass with a PVB laminate inner layer.[364]

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[358] Still, the use of microclimate cases is currently being discusses in the context of sustainable museum strategy debates.

[359] Jerry Shiner, 'Trends in Microclimate Control of Museum Display Cases', in *Museum Microclimates. Contributions to the Copenhagen Conference 19 - 23 November 2007* (Copenhagen: The National Museum of Denmark, 2007), 267–76.

[360] See chapter 3.2.1. for a description of the synergies between ambient oxygen and photodegradation processes.

[361] Saunders, *Museum Lighting*, 121.

[362] Lord and Piacente, *Manual of Museum Exhibitions*, 309.

[363] Freestanding upright glass cases have usually (low-reflective) glass panes with a thickness of 11,5 mm (= 5 inch) (Lord and Piacente, *Manual*, 309).

[364] The thicker the PVB laminate inside the glass pane, the higher is the UV-absorption of the glass pane. National standards for UV-protective glass should be followed (Hilbert, *Sammlungsgut in Sicherheit*, 509)

Figure 39: An example for the use of artificial light sources in a display case in the 'Intercamera' exhibition at the National Technical Museum Prague, Czech Re- public.

Figure 40: Detail of the LED light bar of the display case described in Fig. 34.

Figure 41: LED light bars fixed in a display case to illuminate light-sensitive drawings in the exhibition 'Santini and his World of Architecture (1723-2023)' at the National Technical Museum Prague, Czech Republic.

4.4. Suggestions for a light damage mitigation concept for RSM

Chapter 4.1. to 4.3. gave an overview about possible light damage mitigation solutions to assist decision making for an adequate lighting system for RSM.
The light damage mitigation concept for RSM is based on the research cited in chapter 4., chapter 4.1. and chapter 4.2.

The creation of a light plan for all three exhibition spaces can help to adopt a long-term lighting strategy that mitigates light damage. The categorisation of the RSM collection's sensitivity to light and ultraviolet radiation can be used to enter information of light sensitivity of exhibited objects in the light plan.

<u>Protection measures applied to the outside of the windows</u>

The annual average of daily mean temperature[365] in Chiang Mai is 26.2 °C (79.1 °F). The annual average of mean daily sunshine hours are 6.9 hours per day.[366]

Thus, incoming natural light through the windows of the RSM exhibition spaces should be reduced, ultraviolet and infrared radiation should be eliminated. Adjustable light-impermeable elements in the form of rotating and sliding lamellas are recommended for this purpose. Implementation of an automated daylight control systems is not necessary because there is no skylight in the exhibition spaces.

One option is to completely block the daylight by closing the lamellas and illuminate the exhibition spaces with an artificial light source what emits no ultraviolet radiation. The benefit of this method is that ultraviolet radiation is blocked out in the entire exhibition space. This makes it easier to plan new exhibitions and rotation of the Antiques Collection, because even objects highly sensitive to ultraviolet radiation can be displayed in such a room without additional pro- tection through display cases or glazed frames (except if they are necessary for other reasons such as climate control).[367]

If daylight is explicitly desired for the lighting design, a separate exhibition area should be created near the windows in which insensitive material groups, such as glazed ceramics or unpainted stone sculptures, are displayed. To achieve this, the lamellas can be adjusted so that daylight is reduced, but sufficient illuminance is available to illuminate the exhibition near the windows with natural light. However, care must be taken to monitor closely and possibly regulate the temperature and relative humidity in the separated exhibition area near the windows.

[365] The annual average daily mean temperature is s a climatological measure that represents the average of all the daily mean temperatures recorded at a certain location over a year.

[366] Data published by Royal Irrigation Department of Thailand based on measurements executed from 1981–2010.

[367] Saunders, *Museum Lighting*, 209.

Protection measures applied on or to the inside of the windows

If an illumination with natural light near the windows is to be planned, to block the sunlight's UV-radiation and IR-radiation a suitable functional fabric should be mounted on the inside of the windows.[368] This fabric should be vapour-coated on one side with metals such as aluminium or steel and a desired degrees of transparency of the fabric can be chosen.[369]

Protection measures applied to the light source

The RSM Management's decision to use LEDs adjustable[370] from 50 to 300 lx with UV-filter for room illumination will reduce UV exposure to a minimum.

Protection measures applied to the display case

As described in the last chapters, there are many ways to reduce light levels by exhibition architecture decisions. Show cases in particular may be used to ensure the protection of light-sensitive objects, because display cases can be used to add an additional UV-protection between room light and object.

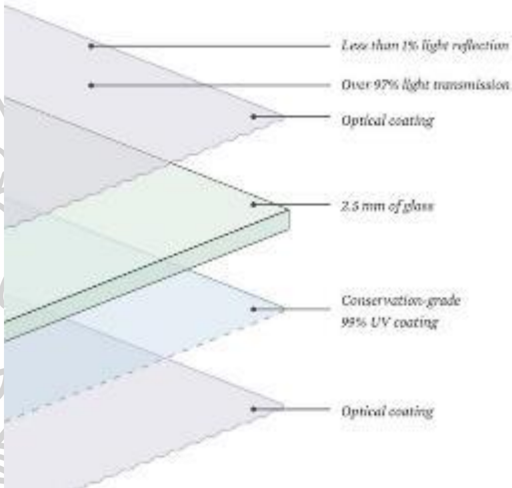

Figure 42: The composition for PVB-laminate containing glass for display cases

For the show cases glass panes with a thickness of 11,5 mm (= 5 inch) should be chosen.[371] The thicker the PVB laminate inside the glass pane, the higher is the UV-absorption of the glass pane. National standards for the thickness of PVB foils in the UV-protective glass should be followed. The glass should be low-reflective.[372]

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368 Saunders, *Museum Lighting*, 279.

369 An example of a European company is Company Création Baumann, silver, and steel - fabrics for regulating light and warmth, product catalogue 2015, Leopold Editionen, Sitzmöbelstudio-Einrichtungen, Handelsgesellschaft m.b.H., Fiedlerstraße 2-4, 4040, Austria.

370 Most likely LEDs from ERCO company will be chosen, https://www.erco.com/en/.

371 Lord and Piacente, *Manual of Museum Exhibitions*, 309.

372 For example: Tru Vue, Museum Glass®.

Moreover, freestanding cases with integral lighting hoods have the benefit, that a specific lighting situation for highly sensitive objects can be created.

The decision for the use of actively or passively controlled show cases should depend on the planning of adequate environmental condition in the exhibition spaces.

Protection measures applied to the art object

UV-protective glazing in the frames of highly light sensitive flat objects like drawings or paintings should be considered (especially if light levels in their surrounding cannot be kept according to the guidelines). Like in the case of the display cases also for glazed frames UV-protective glass according to national standard and of appropriate thickness. Moreover, the glass should be low-reflective.

Improvement of viewing conditions

During the planning of the exhibition design optimising of the viewing conditions should be considered. Further, display areas for highly light sensitive objects should be created. Periodic lighting (turning off or dimming the light when no visitor is detected by a nearby proximity switch) can be used in this context. Shielding objects from light in specifically designed drawers or covered display cases is especially recommended for objects containing highly sensitive colourants or low-quality paper.

However, it is advised to educate museum staff about the risks of light damage and to train them in best practices for light damage mitigation.

Finally, regular monitoring, as mentioned in the next chapter, is suggested.

4.5. Suggested monitoring

4.5.1. Monitoring of light damage

Light, ultraviolet and – when using natural light for exhibition lighting – infrared levels and finally light exposure (lx h) should be monitored.

Light and UV levels should be measured with the instruments introduced in chapter 2.3 on monitoring points defined in the light plan. To simplify the monitoring process light loggers may be used (Fig. 43).[373] Light loggers measure light and UV values in at regular intervals and collect the data on these measurements. This data can be used to analyse the light situation of a certain place in the exhibition. To collect data on the illumination of a certain reference object the logger should be placed as close as possible to the object.[374]

Moreover, small monitoring probes[375] are available, that can be connected with a cable to a WiFi data logger. These small probes allow a descrete monitoring and can be used even in small showcases (Fig. 44).

Further, exposure records of exhibited objects should be kept in lux hours (lx h). Detailed exposure records are crucial for tracking the total amount of light an object has received over time. On basis of data collected by the monitoring the yearly exposure budget of an object can be calculated.

[373] For example Testo™ '160 THL - WiFi data logger' with integrated sensor for temperature, humidity, illumination levels and ultraviolet radiation, https://www.testo.com/en-UK/testo-160-thl/p/0572-2024.

[374] Saunders, *Museum Lighting*, 244.

[375] For example Testo™ 'Lux and UV probe for monitoring light-sensitive exhibition objects', https://www.testo.com/en-UK/lux-and-uv-probe-for-monitoring-light- sensitive-exhibition-objects/p/0572-2157.

Figure 44: Example of an illumination level and ultraviolet radiation WiFi data logger

Figure 43: Example of an illumination level and ultraviolet radiation monitoring probe.

Monitoring of changes to the collection

Measuring colour change in collection can be achieved with different monitoring tools.

The CCI Light Damage Calculator[376] can assist monitoring by visualising the colour change to common pigments and dyes.

Monitoring with ISO Blue Wool Standard cards:

The use of Blue Wool Standard reference cards (Fig. 45) offers a practical and effective method for assessing and managing light exposure. These cards feature a series of blue-dyed wool strips with varying degrees of lightfastness. The fading of these strips provides a visual indication of light damage, helping conservators make informed decisions about display and storage conditions.[377]

The blue wool scale cards willl normally be used in conjunction with grey scale cards in order to assess the degree of change.[378]

Figure 45: Example of an ISO Blue Wool reference card.

[376] 'Light Damage Calculator', Government of Canada, June 11, 2013, https://app.pch.gc.ca/application/cdl-ldc/de-scription-about.app?lang=en.

[377] Saunders, *Museum Lighting*, 96.

[378] BWS cards can be bouth for example at Talas Conservation, Archival and Bookbinding Supplies, https://www.talasonline.com/Blue-Scales-Textile-Fading-Car

4.5.2. Suggestions for a light damage monitoring at RSM

For the RSMs three exhibition spaces a light- and UV- monitoring with illumination level and ultraviolet radiation WiFi data logger at strategicly chosen points in as close as possible to most sensitive objects on display is recommended.[379]These most sensitive objects are listed in chapter 1 in the category ‘highly sensitive to visible light’.

Further, it is recommended to monitor changes to the collection on display with Blue Wool Standard cards. When choosing monitoring points for BWS cards in a gallery or museum setting, it's essential to consider the location's light exposure. The cards should be placed in areas representative of the different lighting conditions within the space. This could include areas with direct exposure to natural light, spaces under artificial lighting, and more protected areas. By comparing the degree of fading on the Blue Wool cards from different locations, conservators can assess the relative risk of light damage throughout the gallery or museum.[380]

The monitoring intervals for checking the Blue Wool cards can vary based on the specific conditions of the exhibition space and the sensitivity of the objects on display. However, a general recommendation is to check the cards periodically, for instance, every few weeks to every few months. This frequency allows for timely detection of significant changes in light exposure and the potential for light damage. D. Saunders' ‘Museum lighting’ emphasises the importance of understanding the light sensitivity of different materials and using appropriate conservation strategies to mitigate light-induced damage.[381]

In summary, the proactive monitoring of light exposure using tools like Blue Wool Standard reference cards, coupled with strategic placement and regular assessment, is crucial in preserving the integrity of valuable collections.

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[379] Saunders, *Museum Lighting*, 239–45.

[380] Saunders, *Museum Lighting*, 96.

[381] Saunders, *Museum Lighting*, 97.

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Appendix I Product data sheets

Data sheet
testo 545

Be sure. testo

Lux meter

testo 545 – Digital Lux measuring instrument with App connection

- Simple, fast and precise measurement of illuminance (Lux) according to the V-lambda curve for all common light sources
- Wide range of applications due to LED compatibility (except single-color blue LED)
- Fast in-app configuration, graph history, second screen and measurement data memory in the testo Smart App
- Audible alarm sounds if a limit value is exceeded
- Timed and point mean value calculation

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Illuminance is a decisive factor for productivity, well-being and health, especially in workplaces. Light sources that are too bright dazzle, while those that are too dark can lead to concentration problems and headaches.

With the Lux meter testo 545 you can measure the **illuminance of all common light sources** - quickly, easily and precisely. The measuring instrument is compatible with almost all commercially available LEDs
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Ordering data / technical data / accessories

testo 545

testo 545, Lux measuring instrument with App connection and audible alarm, incl. transport bag, calibration protocol and 3 x AA batteries

Order no. 0563 1545

Sensor type	Silicon photodiode
Measuring range	0 to 100,000 lux
Accuracy ±1 digit	±3% of m.v. ±1 digit (Class C, corresponding to DIN 5032-7 / EN 13032-1, Appendix B f1 = 6% = V(Lambda) adjustment f2 = 5% = cos-true evaluation Total ≤15%)
Resolution	0.1 Lux (< 10,000 Lux) 1 Lux (≥ 10,000 Lux)
General technical data	
Operating temperature	Measuring instrument: 14° to 122 °F Probe: 0° to 122 °F
Storage temperature	14° to 122 °F
Battery type	3 x AA
Battery life	70 h
Dimensions	Measuring instrument: 5.9 x 2.4 x 1.1 in Probe: 5.3 x 2.1 x 0.9 in Cable length 4.6 ft
Weight	0.63 lbs
Protection class	Measuring instrument: IP 40 Probe: IP20
Housing material	ABS + PC / TPE

The testo Smart App

- Simple and fast: Measurement menus for numerous applications provide optimum support in configuring and carrying out the measurement
- Clear graphical presentation of readings, e.g. as a table, for quick interpretation of results
- Create digital measurement reports including photos as PDF/CSV files on site and send via e-mail

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testo SMART

Accessories	Order no.
testo Bluetooth® printer, incl. 1 roll of thermal paper, rech. battery, power supply	0554 0621
Spare thermal paper for printer (6 rolls), measurement data documentation can be read for up to 10 years	0554 0568
ISO illuminance calibration certificate Calibration points 0; 500; 1000; 2000; 4000 lux	0520 0010
NIST Light Calibration Certificate	400520 8501

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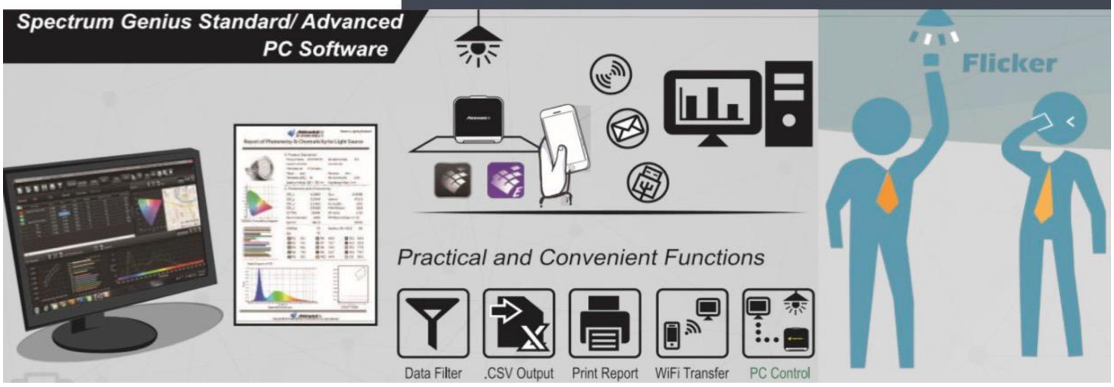
- The receivers install our APPs on smart devices, open the .ast file with the APP and can easily review the data of the measurement.
- NIST traceable, verification and criterion, the output wavelength pitch is 1nm displayed with high-resolution in full color screen.
- Auto dark calibration, this advanced technology allows users to automatically re-calibrate the meter during boot ups.
- Social media integration, users can share measurement data via social media including: Twitter, Facebook/Messenger, WeChat, Line, WhatsApp, SMS and others.
- Applicable mobile devices: iOS devices like iPhone, iPod touch 5, iPad and all Android devices 4.4.2 and above version.

Updated: Jan 2017



PC software

“Spectrum Genius Standard” and “Spectrum Genius Advanced” are PC softwares for operating professional data analysis on data taken by Lighting Passport Pro. They allow users to import multiple measurement results for further analysis, then output them into professional reports.

The Advanced version has a huge library of reference spectrums for users to benchmark with their imported measurement data.

<table>
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(Standard/Advanced)</td><td>CIE x,y,u′,v′
CCT
*Duv
CRI (RA) (R1-R8)
*Re (R1-R15)
R1-R15 Radar/Bar Chart
CQS
Q1-Q15
TLCI (Qa)
GAI
Illuminance
Foot Candle
*PPFD</td><td>CIE 1931/1976 Diagram
Peak Wavelength (λp)
*Dominant Wavelength (λD)
*Purity
FWHM
*SP ratio
C78.377-2008 Diagram
IEC-SDCM Diagram
Spectrum Diagram
Flicker Index
Flicker Percentage
Flicker Frequency
*TM-30-15</td></tr>
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(Standard/Advanced)</td><td colspan="2">PC control Measurement, Data Filter, CSV Output, DAT Output, Print Report, Automatically Record Temperature & Humidity, Precision Mode, GPS Orientation</td></tr>
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(Advanced Only)</td><td>Multi CIE 1931 Display
Multi CIE 1976 Display
Multi Spectrums Display</td><td>Multi C78.377-2008 Display
Multi IEC-SDCM Display
Multi GPS Map Display</td></tr>
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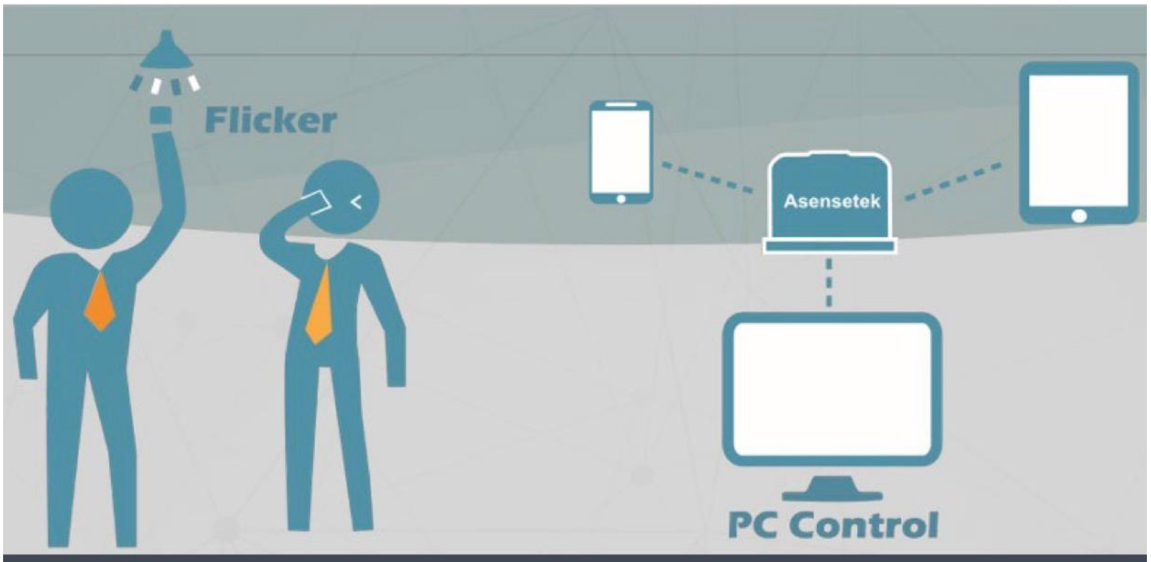
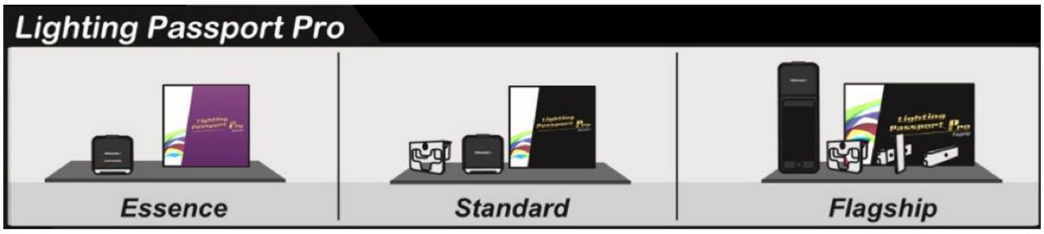


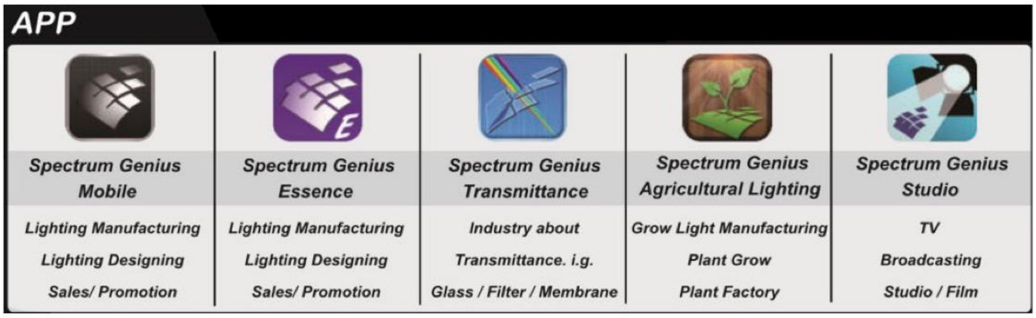
Specifications

Product type	Pro Essence	Pro Standard	Pro Flagship
Size	Width: 68,5mm Depth: 17mm Height: 56mm		Width: 68,5mm Depth: 17mm Height: 189mm (Includes iPod touch)
Net Weight	79 g ± 1g		214 g ± 1g
Wavelength Range	380 ~ 780 nm		
Illuminance Range	Measurable: 5 ~ 50000 lux Reliable Chromaticity: 100 ~ 50000 lux	Measurable: 5 ~ 50000 lux Reliable Chromaticity: 50 ~ 50000 lux	
Output Wavelength Pitch	1 nm		
Optical Resolution(FWHM)	10 nm	8 nm	
Repeatability (2σ)	* x, y: <0.001	* x, y: < 0.0005	
Accuracy (@1000 lux Standard Light Source)	x,y: ± 0.003 Illuminance: ± 5 % CCT: ± 3 %	x,y: ± 0.002 Illuminance: ± 3 % CCT: ± 2 %	
Flicker Measurement Capability	Range: 5 ~ 200 Hz Accuracy: ± 5 %		
Integration Time	6 ms ~ 16 s		
Operation Temperature/ Humidity Range	0 ~ 35 °C, relative humidity 80 % with no condensation		
Storage Temperature/ Humidity Range	-10 ~ 45 °C, relative humidity of 85 % or less (@ 35 °C) with no condensation		
APPs	SGE, SGT, SGAL, SGS	SGM, SGT, SGAL, SGS	

* In Precision Mode (@ 1000 lux Standard Light Source)

Lighting Passport Product Collection





VITA

NAME	Aurelia Berger
INSTITUTIONS ATTENDED	University of Applied Arts Vienna, Institute of Conservation 1st October 2013 - 29th July 2018 Diploma studies in Conservation, specialization paintings (Award of the diploma certificate on 29th June 2018) Award of Merit scholarship (2015/16)
	University of Vienna and University of Salzburg in cooperation with BlueShield 7th August 2016 - 14th August 2016 Summer school : UNESCO world Heritage, Cultural Property Protection and Communication
	University of Vienna, Department of Art History 1st October 2008 - 19th January 2015 Bachelor's degree in art history (award of bachelor's degree on 19th January 2015)
PUBLICATION	Tupy, A./ Berger, A., Ein Scagliolabild aus dem stift Neukloster, in: Krist, G./ Wilk, H., Depotoffensive. Wiener Neustadt - Zwett - Eggenburg - Purgstall - Komeuburg - Retz, Band, 14, Wien 2017, S. 307 – 316