EXPLORING EFFECTS OF LIGHTING IN PHYSICAL AND VIRTUAL SPACES

Vom Fachbereich Sozialwissenschaften der
Rheinland-Pfälzischen Technischen Universität,
Kaiserslautern-Landau

zur Verleihung des akademischen Grades
Doktor der Philosophie (Dr. phil.)
genehmigte

Dissertation

vorgelegt von
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Tag der Disputation:	Kaiserslautern, 13. Juni 2023
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Juni 2023

"In many ways, human-centric lighting is new land waiting to be explored. As with any exploration, it would be unwise to rush out into the wilderness without careful preparation. Preparation requires knowledge and this can only be gained by careful research into the importance, magnitude and reliability of the effects. It is only in this way that successful exploration can be ensured."

Peter R. Boyce (2016, p. 101)

Remarks

An excerpt from the theoretical explanations in Chapter 2 and 3 was published in "Ronft, S. (2021). Visuelle Kommunikation bei Veranstaltungen. In S. Ronft (Ed.), Eventpsychologie: Veranstaltungen wirksam optimieren: Grundlagen, Konzepte, Praxisbeispiele (pp. 201–230). Springer Gabler. https://doi.org/10.1007/978-3-658-28888-4_10"

Part II 12 is being prepared for publication in *Frontiers in Psychology, Section Environmental Psychology*, by Steffen Ronft, Thomas Lachmann, Ann-Kathrin Beck, and Tandra Ghose. All experiments in Part II were conducted under the supervision of Tandra Ghose in Ghose Perception Laboratory Kaiserslautern.

Chapter 7 was presented at the European Conference on Visual Perception (ECVP) Trieste by Steffen Ronft and Tandra Ghose (2018).

Chapter 8 was presented at the European Conference on Visual Perception (ECVP) Leuven by Steffen Ronft and Tandra Ghose (2019).

Chapter 11 was presented at the LiveCom-LAB Conference, Giessen by Steffen Ronft and Ann-Kathrin Beck (2022).

Chapter 11 was published as "Ronft, S. & Beck, A-K. (2023). Understanding psychological mechanisms to improve virtual spaces and Metaverse events. *LiveCom-LAB Conference Proceedings*, [in press]"

Chapter 12 is being prepared for publication as "Exploring effects of lighting in virtual spaces on perception and quality of stay" by Steffen Ronft, Ann-Kathrin Beck, and Xin Ying.

The citation style used in this PhD thesis follows the guidelines set out in the 7th edition of the American Psychological Association (APA) style guide (2020).

Abbreviations

Abbreviation or symbol	**Definition**
%	Percentage
3D	3-Dimensional
AI	Artificial intelligence
AMOLED	Active matrix organic light emitting diode
ANOVA	Analysis of variance
ANSI	American National Standards Institute
APA	American Psychological Association
AR	Augmented reality
CAGR	Compound annual grow rate
CCT	Correlated color temperature
Cd	Candela
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CH1	Conflict handling Study 1
CH2	Conflict handling Study 2
CH3	Conflict handling Study 3
CI	Confidence interval
CIE	Commission Internationale de l'Éclairage (International Commission on Illumination)
COVID	Coronavirus Disease
CRI	Color rendering index
CTO	Color temperature orange
d	Cohen´s measure of effect size
DCI	Digital Cinema Initiative
df	Degree of freedom
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DOI	Digital object identifier
DV	Dependent variable
ECG	Electrocardiography
EDA	Electrodermal activity
EEG	Electroencephalography
E_v	Illuminance

F	F distribution
$F(v_1,v_2)$	F distribution with v_1 and v_2 degrees of freedom
fEMG	Facial electromyography
FER	Facial expression recognition
GDP	Gross domestic product
GHz	Gigahertz
GLM	Generalized linear model
H0	Null hypotheses
H1	Alternative hypotheses
HCL	Human-centric lighting
HCVL	Human-centric virtual lighting
HDR	High dynamic range
HMD	Head mounted display
HRV	Heart rate variability
HSD	Tukey´s honestly significant difference
Hz	Hertz
IDC	International Data Corporation
IES	Illuminating Engineering Society
IF	Image forming
IGL	Intergeniculate leaflet
ILV	International lighting vocabulary
ipRGC	Intrinsic photosensitive retinal ganglion cells
IPS	In-Plane switching
IQR	Interquartile range
IR	Infrared
ISO	International Organization for Standardization
IV	Independent variable
I_v	Luminous intensity
IVE	Immersive virtual environment
K	Kelvin
LCD	Liquid crystal display
LED	Light-emitting diode
LGN	Lateral geniculate nucleus
LL	Lower limit
lm	Lumens

lx	Lux
M	Mean
Mo	Mode
Mdn	Median
MICE	Meetings, Incentives, Congresses / Conferences, Events /Exhibitions
Ms	Millisecond(s)
MVA	Multi vertical alignment
N	Total number of cases
n	Number of cases (in subsample)
NIF	Non-image forming
nm	Nanometers
OLED	Organic light emitting diode
p	Probality
PAD	Pleasure / Arousal / Dominance
PANAS	Positive Affect Negative Affect Scales
PC	Personal computer
PCA	Principal component analysis
PVA	Patterned Vertical Alignment
PwC	Pricewaterhouse Coopers
Q(D)-OLED	Quantum-dot organic light emitting diode
Q_v	Luminous energy
R	Multiple correlation
R_a	$\text{Referenzindex}_{\text{allgemein}}$ (Color rendering index)
r	Pearson´s correlation / effect size of Wilcoxon signed-rank test
R^2	Multiple correlation squared; measure of strength of association
RGBW	Red green blue white
RHT	Retinohypothalamic tract
SAD	Seasonally affective disorder
SAM	Self assessment manikin
SCL	Skin conductance level
SCN	Suprachiasmatic nuclei
SD	Standard deviation
SE	Standard error
SEM	Structural equation model

SI	Système international (International System of Units)
sRGB	Standard red green blue
SS	Sum of squares
t	*t*-test value
T	Wilcoxon test value
T_c	Color temperature
TKI	Thomas-Kilmann instrument
TN	Twisted Nematic
TR	Technical reports
TS	Technical specification
U	Mann-Whitney test statistic
UL	Upper limit
USD	United States Dollar
UV	Ultraviolet
VAS	Visual analogue scale
VL1	Virtual lighting Study 1
VL2	Virtual lighting Study 2
VL3	Virtual lighting Study 3
VR	Virtual reality
W	Watt
z	z-score; value of a statistic divided by its standard error
α (alpha)	in statistical hypothesis testing, the probability of making a Type I error; Cronbach´s index of internal consistency
β (beta)	in statistical hypothesis testing, the probability of making a Type II error ($1 - \beta$ denotes statistical power)
Δ (delta)	Increment of change
η^2 (eta squared)	Measure of strength of relationship
λ (lamda)	Goodman-Kruskal measure of predictability; element of factor loading matrix; wavelength
Σ (capital sigma)	Summation
Φ_v (phi)	Luminous flux
X^2 (chi squared)	Chi square distribution
Ω (omega)	Solid angle in steradians

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1. Introduction

Light is an essential aspect of daily life and affects a range of physiological and behavioral processes, including circadian rhythms, alertness, cognition, mood, and behavior. The impact of lighting on daily life has been accelerated by technological advances such as light emitting diodes (LEDs). Access to electric and modern lighting systems is increasing globally, and the scientific exploration of human-centered effects of lighting can serve the billions of people worldwide who are exposed to natural and electric lighting in their daily lives. Decades of interdisciplinary research drawing on findings from various fields such as physics, engineering, psychology, medicine, business administration, and architecture have already explored the biological and psychological effects of lighting and have indicated the significant potential for further advancements in this field. According to Vetter (2022, p. 398), "there is enormous potential to improve human health, performance and wellbeing via the development of innovative lighting technologies and strategies that address these effects."

Beyond lighting in physical spaces, three-dimensional virtual environments such as metaverse platforms, spurred by the need for digital meeting spaces during the COVID-19 pandemic, are becoming increasingly important and are already being integrated into daily life for personal or professional purposes. In such virtual spaces, simulated lighting scenarios are used that can have visual and non-visual effects on users. It can be assumed that the number of people affected by this will also increase rapidly due to technological progress, emerging applications, more affordable prices, and more widespread economic growth and digitalization beyond currently industrialized countries. Overall, the exploration of human-centered lighting effects offers an exciting opportunity to improve the quality of life for people worldwide.

After this brief introduction (Chapter 1), the contemporary state of research on lighting and its influences on humans is reviewed (Chapter 2). After illustrating research methods in lighting research (Chapter 3), an interim conclusion (Chapter 4) is derived and research gaps are noted.

The second part of the thesis is dedicated to the investigation of effects of lighting on complex emotional and behavioral constructs such as conflict handling (Chapter 5). The effects of lighting as an independent variable are examined in elaborate laboratory experiments with realistic correlated color temperature (CCT) levels (Study CH1, Chapter 6) with 68 participants and under enhanced CCT changes with 68 participants (Study CH2, Chapter 7). A cross-study examination of the collected data (Study CH3, Chapter 8), discussion (Chapter 9), and an overall conclusion (Chapter 10) complete this exploration. By using established and advanced statistical procedures such as an ANOVA test, factor analyses, and a structural equation model, the effects are examined in-depth and critically discussed.

The third part of the thesis addresses the exploration of lighting in virtual spaces, which has gained a tremendous growth of importance during the preparation of this thesis. This is due to an interplay of technical developments, changing usage habits and interest in virtual meetings in the context of COVID-19 pandemic and international public debate on metaverse applications. After a review of the literature and presentations on methodological approaches and challenges (Chapter 11), own studies are conducted.

An international study with 95 participants (Study VL1, Chapter 12), which was unrestrictive in terms of subject sample and technological components, gathers initial insights into the use of measurement instruments and visual and non-visual effects of lighting in virtual environments. A subsequent laboratory study (Study VL2, Chapter 13) with a homogeneous sample of 106 participants under controlled conditions both validates the first study as well as offers further findings, especially regarding preferences in the design of virtual environments.

For this purpose, an ANOVA test and a Wilcoxon signed-rank test for nonparametric data are used in addition to descriptive and frequency analyses. The data from both studies are systematically compared to conclude the exploration (Study VL3, Chapter 14). After a critical discussion (Chapter 15) of the general research findings and the limitations of the previous studies, implications for research and practice – up to the interdisciplinary perspective of a novel approach of human-centric virtual lighting (HCVL) – are derived. A general discussion and brief conclusion (Chapter 16) complete the thesis.

PART I: CURRENT STATE OF RESEARCH

This part of the thesis presents the current state of lighting research, introduces definitions and delimitations, and illustrates the effects of lighting in special contexts. After outlining the methods employed in lighting research, an interim conclusion highlights research gaps. These research gaps form the premise of the subsequent parts of this thesis, including both the theoretical background and original experimental studies.

2. (Human-centric) lighting and visual perception

2.1 Definitions of light and lighting

Terms that initially appear trivial such as light or illumination are difficult to define in a generally valid manner because different approaches and delimitations matter. International organizations play a special role in delimiting the definitions of terms in technology, practice, and lighting research; discussing these terms; and adapting them to current developments. Organizations such as the American National Standards Institute (ANSI), the Commission Internationale de l'Eclairage (CIE), the Illuminating Engineering Society (IES), the European Committee for Standardization (CEN) and the International Standardization Organization (ISO) are primarily responsible for specifications and standards in the field of lighting. In some cases, they collaborate and publish joint statements, standards, and vocabularies.

According to the definition of ANSI and IES, light is “Radiant energy that is capable of exciting the retina and producing a visual sensation in humans. The visible portion of the electromagnetic spectrum extends from about 380 to about 780 nanometers” (American National Standards Institute [ANSI] & Illuminating Engineering Society [IES], 2019). The International Illumination Vocabulary (ILV), administered by the CIE, again separates the definition of light into psychophysical versus photometric perspectives: (1) “Light (psychophysical): radiation that is considered from the point of view of its ability to excite the visual system” (Commission Internationale de l’Eclairage [CIE], 2020a) versus (2) “Light (photometric): radiation within the spectral range of visible radiation” (CIE, 2020a). The usage of the term “light” as a synonym for optical radiation covering the spectral range from X-ray spectral range lower than 1 nm up to 1mm is referred to as a misuse by the CIE is referred to as misuse by CIE (2020a) and should be avoided.

In a position paper regarding non-visual effects of light the CIE (2019) states that these effects comprise “any electromagnetic radiation that can create a visual sensation by directly stimulating the retinal photoreceptors of the visual system. In addition to enabling vision, these photoreceptors also drive biological effects that powerfully regulate human health, performance and well-being.” This definition thus includes both the visual and non-visual effects of lighting. A more detailed explanation and distinction between visual and non-visual effects, also termed image forming (IF) and non-image forming (NIF) effects, is offered in Section 2.3. In lighting research, the relevant range of wavelengths is usually assumed to be 400 nm to 700 nm (Houser et al., 2021) or 380 nm to 780 nm according to the ANSI and IES (2019) definition. This work therefore follows a definition of light as a physical stimulus in the wavelength range from 380 nm to 780 nm that can elicit visual and nonvisual responses.

Daylight is defined as “part of global solar radiation capable of causing a visual sensation” (CIE, 2020a), where global solar radiation is summarized as "[...] direct solar radiation and diffuse sky radiation" (CIE, 2020a). Accordingly the terms sunlight, skylight, and daylight can also be differentiated as "part of direct solar radiation that can cause visual sensation" (CIE, 2020a), "part of sky radiation that can cause visual sensation" (CIE, 2020a), and as "part of global solar radiation that can cause visual sensation" (CIE, 2020a), respectively.

Likewise, the central term "lighting" requires a general definition, which is provided by CIE as a recognized authority: “Lighting [is the] application of light to a scene, objects, or their surroundings” (CIE, 2020a). This general definition can be further differentiated through various considerations, such as the type of light source or the field of application.

“Daylighting" refers to lighting in which daylight is the light source; the alternate term "natural lighting" used and discussed for this purpose until 2020 is deprecated as a standard term (CIE, 2020a). “Electric lighting” refers to "lighting provided by electric light sources" and replaced “artificial lighting” in 2020 (CIE, 2020a). The term “integrative lighting”, also called human-centered lighting, is used to describe “lighting integrating both visual and non-visual effects, and producing physiological and/or psychological benefits upon humans” (CIE, 2020). A detailed presentation of this human-centered concept is given in subsequent chapters.

Lighting quality is defined as the “degree of excellence to which the totality of lighting characteristics fulfils user needs and expectations or other applicable requirements” (CIE, 2020a). The degree of excellence in this formulation is not a quantitative measure but depends on the application area and includes the individual well-being of the end user, safety and public security, architecture, and the illuminated environment (CIE, 2020a).

2.2 Light parameters and designing variables

The following sections briefly describe particularly relevant parameters and variables for lighting design.

Categorization

Light and lighting conditions are difficult to describe due to numerous variables and possible affecting factors in visual perception. As such, various parameters are needed to have comparable lighting situations. A final categorization does not exist, but according to Houser et al (2021) the following four categories can be distinguished in lighting design: (1) light spectrum, such as color temperature and chromaticity; (2) spatial patterns, such as luminance distribution; (3) light level, such as luminance; and (4) temporal patterns, such as duration of exposure.

Correlated Color Temperature (CCT)

The definition of the color of light refers to the position of the black-body curve, which is based on Planck's law of radiation and describes the radiation intensity of an ideal black body (CIE, 2020a). The color temperature of white light is reported as Correlated Color Temperature (CCT) in Kelvin (K). A CCT value below 3,300 K is described as warm lighting, whereas CCT values around 4,000 K are neutral and higher values above approximately 5,300 K are described as cold or daylight (see Fig. 1; Greule, 2015). However, there is no general definition at which Kelvin values these semantic distinctions are made.

Figure 1

Characteristics of light sources regarding typical CCT

Warm white **< 3,300 K**	**Neutral white** **3,300 K – 5,300 K**	**Cold white/ daylight** **> 5,300 K**
Sunrise / sunset 2,000 K – 3,000 K	Morning / evening sun 3,500 K – 5,000 K	Cloudy sky 5,500 K – 8,000 K
Candle 1,500 K	High-pressure mercury vapor lamp 3,400 K – 4,200 K	Blue sky 8,000 K – 12,000 K
Incandescent lamp 2,700 K	Xenon lamp 4,500 K – 5,000 K	Fluorescent tube 5,500 K – 8,000 K

Note. All values are approximate. LED lighting with additive color mixing provides an unlimited range of CCT levels. Adapted by Greule, 2015, p. 29; Ronft, 2021b, p. 217.

Chromaticity

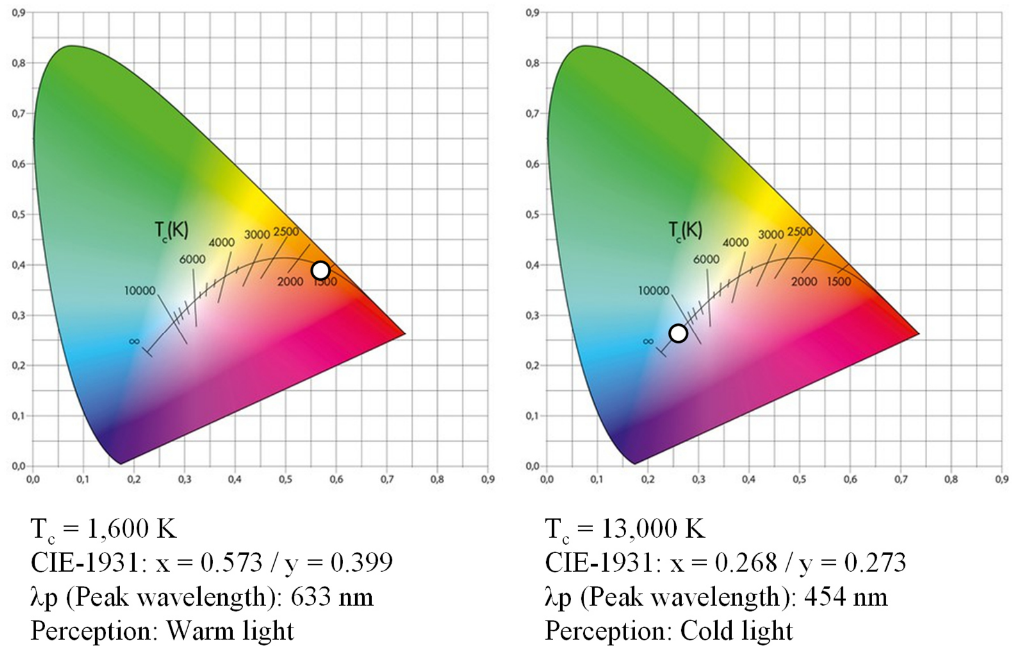
Chromaticity is defined as the “property of a colour stimulus defined by its chromaticity coordinates, or by its dominant or complementary wavelength and purity taken together” (CIE, 2020a). Thus, chromaticity gives an objective specification of the quality of a color regardless of its luminance.

Color space (CIE-1931)

The representation method in the CIE-1931 color system (see Fig. 2) is the most common perception-related form of representation, though other systems (CIE-1964; CIE-2015) have already been developed through further measurement phases. The CIE-1931 system allows the description of colors by means of x (red), y (green), and z (blue) values on the CIE chromaticity diagram. The basic condition x + y + z = 1 is valid, allowing the z-value to be omitted by transformation. The diagram contains the black body curve, which refers to Planck's radiation law and describes the radiation intensity of an ideal black body. This system makes it possible to assign a color temperature to the emitted light.

Figure 2

CIE-1931 diagram visualizing different correlated color temperatures



Note. Adapted by Ronft, 2021b, p. 215.

Color Rendering Index (CRI)

The CRI (German: Referenzindex$_{allgemein}$ [R_a]) provides information on the extent to which the coloration of an object and the environment are faithfully reproduced and thus recognizable to the viewer. In essence, the higher the color rendering index, the better the color reproduction. CRI is the "measure of the degree to which the psychophysical colour of an object illuminated by the test illuminant conforms to that of the same object illuminated by the reference illuminant, suitable allowance having been made for the state of chromatic adaptation" (CIE, 2020a). A change in color temperature also leads to a change in color rendition (see Table 1).

Table 1

Relationship between color temperature and color rendering

Color Attribution	CCT [K]	CRI [R_a]
Cold / Daylight	> 5,000	80 – 100
Neutral	3,300 – 5,000	70 – 79
Warm	< 3,300	0 – 69

Note. Adapted by Greule, 2015, p. 85; Keller & Weiß, 2010, p. 47; Ronft, 2021b, p. 217

Flicker [Hz]

Flicker means the "perception of visual unsteadiness induced by a light stimulus the luminance or spectral distribution of which fluctuates with time, for a static observer in a static environment" (CIE, 2020a). Due to the inertia of light-sensitive receptors, people can perceive flicker below 100 Hertz (Hz; (Kelly, 1961; Khanh et al., 2022)). At frequencies above this, the lighting stimuli appears continuous. However, stroboscopic effects can still occur during dynamic movements (Bullough et al., 2011; Bullough et al., 2012; Khanh et al., 2022). Neurobiological measurements indicate that flicker can affect brain activity (Berman et al., 1991; Fedotchev et al., 1990), can trigger migraines and headaches (Shepherd, 2010), and can even lead to epileptic seizures (Fisher et al., 2005). Even with subliminal flicker responses to affective and cognitive effects, such as memory performance and recall, have been reported (Knez, 2014).

Glare

Glare describes the "condition of vision in which there is discomfort or a reduction in the ability to see details or objects caused by an unsuitable distribution or range of luminance, or by extreme luminance contrasts" (CIE, 2020a). Glare is divided into two types: disability glare and discomfort glare (Osterhaus, 2005).

(1) Disability glare is an effect of stray light on the eye that reduces vision and visual performance. (2) Discomfort glare causes discomfort but does not necessarily affect visual performance or vision. People usually try to circumvent disability glare that reduces their vision by, for example, changing their position. Discomfort glare that is not noticed can cause fatigue symptoms such as headaches (Osterhaus, 2005).

Hue

Hue is an "attribute of a visual perception according to which an area appears to be similar to one of the colours red, yellow, green, and blue, or to a combination of adjacent pairs of these colours considered in a closed ring" (CIE, 2020a). Hue can also be described quantitatively as a single number corresponding to an angular position about a central or neutral point or axis in a color space coordinate chart or a color wheel; alternatively, hue can be characterized by its dominant wavelength.

Illuminance [lx]

Illuminance (E_v) is the "density of incident luminous flux with respect to area at a point on a real or imaginary surface, where Φv is luminous flux and A is the area on which the luminous flux is incident" (CIE, 2020a).

$$E_v = \frac{\Phi_v}{A}$$

The SI (International System of Units) unit of illuminance is Lux (lx), and “1 lx is equal to the illuminance produced on a surface of area 1 m^2 by a luminous flux of 1 lm [lumen] uniformly distributed over that surface.” (CIE, 2020a)

Luminous flux [lm]

Luminous flux (Φ_v) is the “change in luminous energy with time, where Q_v is the luminous energy emitted, transferred or received, and *t* is time” (CIE, 2020a).

$$\Phi_v = \frac{dQ_v}{dt}$$

The SI unit of luminous flux is lumen (lm). According to the 9^{th} General Conference on Weights and Measures (1948), a lumen is defined as the luminous flux emitted in a solid angle unit (steradian) from a uniform point light source with a luminous intensity of 1 candela (cd; CIE, 2020a).

Luminous intensity [cd]

Luminous intensity (I_v) is the “density of luminous flux with respect to solid angle in a specified direction where Φv is the luminous flux emitted in a specified direction, and Ω is the solid angle containing that direction” (CIE, 2020a).

$$I_v = \frac{\Phi_v}{\Omega}$$

The SI unit of luminous intensity is candela (cd).

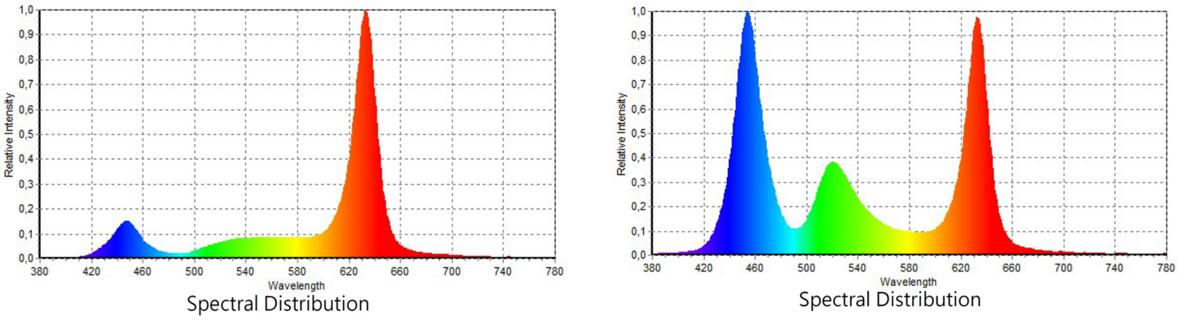
Wavelength [nm]

Wavelength (λ) is the “distance in the direction of propagation of a periodic wave between two successive positions at which the phase is the same” (CIE, 2020a).

Optical radiation generally uses the units nanometer (nm) and micrometer (µm). The wavelengths visible to humans are between 380 nm and 780 nm (ANSI & IES, 2019; Khanh et al., 2022). The spectral composition of the light stimulus is perceived as color. When white light is separated by a prism, the wavelengths appear as visible colors (see Fig. 3). The spectral colors are categorized as seven color terms (Bruno, 2006): violet (380 nm – 449 nm), blue (450 nm – 499 nm), green (500 nm – 569 nm), yellow (570 nm – 589 nm), orange (590 nm – 619 nm) and red (620 nm – 749 nm).

Figure 3

Spectral distribution of white light with high and low CCT by LED



T_c = 1,600 K
CIE-1931: x = 0.573 / y = 0.399
λp: 633 nm
Perception: Warm light

T_c = 13,000 K
CIE-1931: x = 0.268 / y = 0.273
λp: 454 nm
Perception: Cold light

Note. Adapted by Ronft, 2021b, p. 215

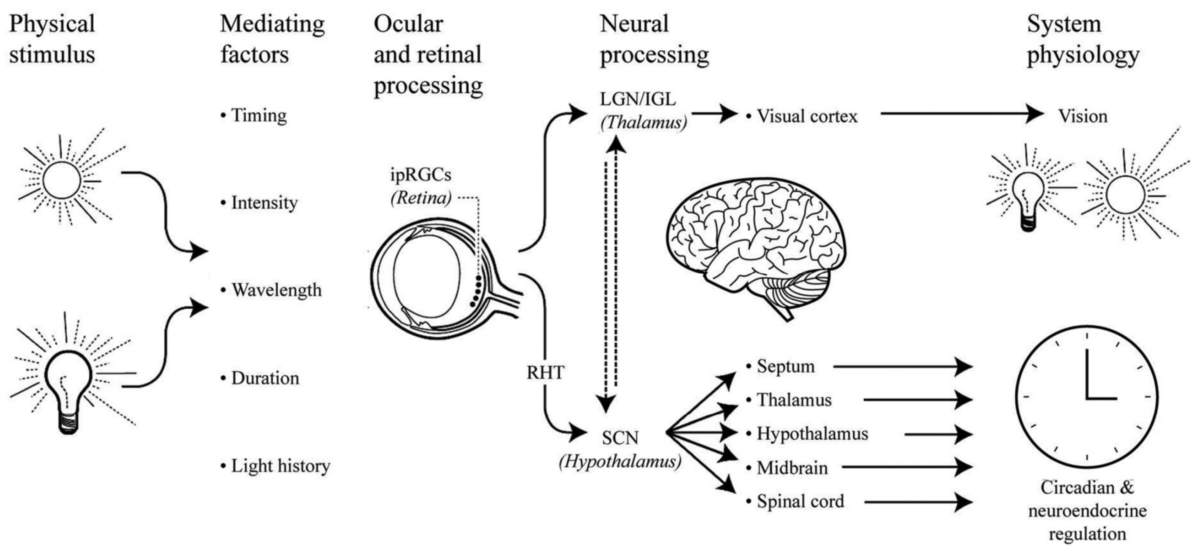
2.3 Image forming (IF) and non-image forming function (NIF)

The fundamental principle of human visual perception is that light enters the eye and stimulates the photoreceptors of the retina. The receptors convert the light information into neuronal signals, which are then transmitted via ganglion cells to different regions of the brain (Vetter et al., 2022). There are three known types of receptors: (1) rods for contrast perception, (2) cones for color perception, and (3) intrinsically photosensitive retinal ganglion cells (ipRGCs), which contain the photopigment melanopsin and are intrinsically sensitive to light stimuli (Berson et al., 2002; Hattar et al., 2002; Provencio et al., 2000; Vetter et al., 2022).

Neural processing of signals can be divided into two categories: an imaging function (IF) and a non-imaging function (NIF), also called non-visual (NV) response (International Standards Organization [ISO] & CIE, 2022). The IF is provided by the optic tract, which employs the optic nerve and chiasm and sends information to image formation structures that include the lateral geniculate nucleus (LGN), the intergeniculate leaflet (IGL), and the visual cortex of the occipital lobe (see Fig. 4). The suprachiasmatic nuclei (SCN), which serve as a biological clock, are supplied with information via the retinohypothalamic tract (RHT), which also serves other regulatory centers of the brain (Gooley et al., 2003; Vetter et al., 2022). The SCN, as the core area of the hypothalamus, is connected to the central nervous system (Hattar et al., 2006; Vetter et al., 2022). However, Houser et al. (2021) highlight that ipRGCs, rods, and cones all influence visual and nonvisual responses in humans.

Figure 4

Schematic illustration of the neuroanatomical underpinnings of physiological effects of light

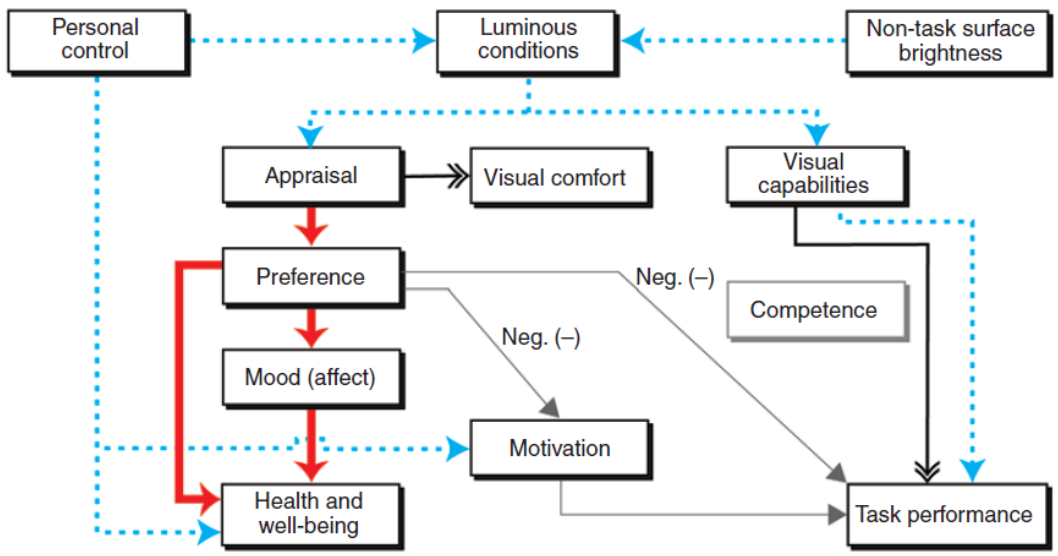


Note. The intrinsically photosensitive retinal ganglion cells (ipRGCs) transmit environmental light information via the retinohypothalamic tract (RHT) to the central clock in the brain (i.e., suprachiasmatic nuclei [SCN]); other direct projections of ipRGCs include thalamic and other brain regions. The response will depends on the light characteristics and/or other mediating factors. LGN: lateral geniculate nucleus; IGL: intergeniculate leaflet (Vetter et al., 2022, p. 388).

Veitch et al. (2008) also differentiate between the psychobiological process called "vision path" and the psychological process called "appraisal path". The linked mechanisms map illustrates the assumed indirect links between lighting and dependent factors such as health, well-being, motivation, mood, and task performance (see Fig. 5). Relationships between luminous conditions, mood, health, well-being, motivation, visual capabilities, and task performance are commonly assumed and examined constructs in psychological lighting research.

Figure 5

Linked mechanisms map of lighting appraisal



Note. Lighting condition test results illustrated with dotted lines, and mediated regression test results shown with solid lines. Heavy solid lines illustrate the appraisal path, while black solid lines with double-headed arrows represent the vision path. The light grey solid lines show extra links, with small effect sizes, added to the model on the basis of the mediated regression results (Veitch et al., 2008, p. 139).

2.4 Defining human-centric lighting (HCL)

Lighting research emerged almost immediately after the introduction of electric lighting technology at the beginning of the 20^{th} century and aimed to improve lighting concepts and technical parameters around the visual performance of people in the context of work and living (Khanh et al., 2022).

In a brief description by Boyce (2016, p. 101), human-centric lighting (HCL) is characterized as “lighting that considers both the visual and non-visual effects of exposing humans to light and that widens the range of possible effects from visual performance and comfort to sleep quality, alertness, mood and behaviour with consequences for human health, learning and spending.”

Following this definition, Khanh et al. (2022) consider the user- and need-centered development of lighting systems and lighting design to be a central task of today's lighting technology and also refer to human-centric lighting as "integrative lighting" (2022, p. 413). The terms "human-centered lighting" and "integrative lighting" can be used synonymously according to CIE (2020a). CIE (2020a) also delineates that integrative lighting can only be applied to humans and that lighting for therapeutic purposes (light therapy) is excluded.

In 2018, Houser recognized issues with the term HCL – which is neither comprehensively defined by an authority such as the CIE nor legally protected as a label – when used in a commercial and industrial context. For this reason, this term can be used by manufacturers and distributors to better market lighting products without fulfilling any lighting quality criteria.

In addition to criticizing the use of an HCL label for marketing reasons, Houser et al. (2021) also point out that the context of use is a crucial factor to appraise the human-centeredness of lighting. For example, a lamp with very high CCT values of 17,000 K may have a useful activating and melatonin suppressing effect in the morning, but its use in the evening will cause sleep disturbance and disrupt the usual circadian rhythm. It is therefore difficult to speak of human-centered lighting in favor of human needs without considering the specific context of application.

The lighting industry offers human-centric products on the market under names such as HCL, dynamic lighting, or circadian lighting. The market for these products is forecasted to grow at a compound annual growth rate (CAGR) of 25%. The global market volume is therefore expected to increase from 1 billion USD in 2020 to 5.5 billion USD by 2027 (Global Market Insights Inc., 2021).

The following seven growth drivers have been identified (Global Market Insights Inc., 2021):

(1) Commercial and healthcare infrastructure transformation activities in North America and the Asia-Pacific region

(2) Growing smart building projects in North America and Europe

(3) Provision of better facilities in the elderly care sector in Europe

(4) Increasing demand for energy-efficient lighting across the globe

(5) Rising implementation of LED lighting solutions in Asia and Latin America

(6) Growing smart city establishments in the Middle East and Africa

(7) Increased focus on implementing advanced lighting technologies in the commercial and industrial settings

Thus, many different growth drivers can be identified internationally that will further strengthen the importance and influence of HCL.

2.5 Lighting and lighting effects in specific contexts

2.5.1 Education and office workspaces

Educational and office workspaces include facilities such as classrooms in schools and universities as well as offices and conference rooms in companies and organizations. Following the definition of the *Cambridge Dictionary*, an office is "a room or part of a building in which people work, especially sitting at tables with computers, phones, etc., usually as a part of a business or other organization" (Cambridge Dictionary, 2022). Industrial workplaces and workplaces in stores are addressed in separate Sections (see 2.5.4; 2.5.5.).

The design of learning spaces (MacConnell, 1951) and especially lighting influences have been a field of research since the 1940s (Hopkinson, 1949; Luckiesh & Moss, 1940).

The objective is to create an environment in which learners can concentrate well and engage in high-performance learning, with a sufficient comfort level for spending several hours indoors. Comparable objectives characterize office workplace design. Especially with regard to the working environment, there are many studies that address the physiological and psychological effects of office lighting. As such, a brief overview of current research areas and results is given in the following paragraphs. The two most important parameters studied regarding lighting in learning and working environments are CCT and luminance.

Ishii et al. (2018) find that the task performance of subjects under high CCT (6,200 K) is better than that of subjects under lower CCT (5,000 K). Shamsul et al. (2013) indicate that their subjects preferred a CCT of 4,000 K, but subjects showed the best subjective attention, including correct typing speed and execution skills, at a CCT of 6,500 K. Keis et al. (2014) demonstrate that a blue-enriched white lighting (4,000 K direct LED lighting with additional CCT 14,000 K indirect LED lighting reflecting from the white ceiling) in classrooms increased the cognitive processing speed and concentration on students.

CCT in particular is an interesting parameter, as low illuminations tend to be perceived as comfortable, but due to the melatonin-suppressing effect (Kraneburg et al., 2017), of higher color temperatures can improve alertness and cognitive performance (Mills et al., 2007). Ye et al. (2018) observe that subjects showed better task performance and higher alertness under illumination at a higher CCT range, which is in line with the results of Smotek et al. (2019) supporting that short-wavelength light enhances cognitive efficiency in task-specific scenarios.

The definition of optimal lighting therefore cannot be generalized but rather depends on tasks, expectations, and space; this aligns with a study by Park et al (2010) in which participants could change a space's color temperature according to its function. A changeable CCT was preferred to constant lighting conditions.

High illuminance level is associated with subjective arousal of the central nervous system (Hawes et al., 2012; Kuller & Wetterberg, 1993). A field study of Hviid et al. (2020) with 92 pupils demonstrated that a change in lighting from 2,900 K at 450 lux to 4,900 K at 750 lux improved students' processing speeds, concentration levels, and mathematical skills.

Based on a post-occupancy study of 1,232 workstations in 64 office buildings, Park et al. (2021) observe that an illuminance of 406 lx for the work surface achieves maximum satisfaction in modern office environments. These results are particularly interesting because certain countries, such as Germany, have regulatory minimum standards for office workplace lighting that must be met. According to the German Institute for Standardization (Deutsches Institut für Normung [DIN], 2021), different minimum lighting requirements apply depending on the activity of the office. For example, conference and meeting rooms must have a minimum of 500 lx; writing, reading, and activities working with monitors must have a minimum of 500 lx; technical drawing activities must have a minimum of 750 lx; reception desks must have a minimum of 300 lx; archives must have a minimum of 200 lx. For all of these activities and spaces, a CRI [R_a] ≥ 80 is specified.

Regarding visual perception, Zhai (2015) implies that illuminance level is more important than CCT.

The effect of lighting has also been studied in early childhood education. Pulay and Williamson (2019) study 3 – 6 year old children and illustrate that, besides CCT and illuminance, other parameters such as the type of light source itself can also be used as independent variables. Pulay and Williamson (2019) distinguish between fluorescent tubes and LED lighting, but other parameters such as illuminance and flicker rate are not reported. These parameters could have psychological and physiological effects in addition to the inherently different spectral distribution of the different light sources. The study reports generally higher child engagement under LED lighting than under fluorescent lighting at a CCT of 4,100 K.

In addition, research is being conducted on learning and productivity, such as the enhancement of creative performance through red or blue accentuated (Kombeiz & Steidle, 2018) or dim lighting (Steidle & Werth, 2013). In the context of applied ergonomics, efforts have been made to improve various aspects of lighting for the benefit of employees (Aries et al., 2020; Bluyssen et al., 2011; Chraibi et al., 2016; Despenic et al., 2017; Hoffmann et al., 2008). The effect of lighting on cognitive performance has also been supported by neuroscientific studies (Chellappa, Gordijn, & Cajochen, 2011; Chellappa, Steiner, et al., 2011; Lehrl et al., 2007; Vandewalle et al., 2009).

Recent studies indicate that electric lighting can inhibit or stimulate self-regulatory (Kang et al., 2019) and cooperative behavior (Kombeiz et al., 2017; Ronft & Ghose, 2019; Steidle et al., 2013; Steidle et al., 2015). Only rarely have studies directly addressed the influence of lighting parameters on self-regulation, cooperation, and negotiation behaviors, which may indicate the need for further research (Baron, 1990; Baron et al., 1992; Kombeiz et al., 2017; Kombeiz & Steidle, 2017). Baron et al. (1992) report inconsistent results, Kombeiz et al. (2017) find that dim, warm lighting activates interdependent self-concepts and promotes collaborative conflict styles. It would therefore be beneficial to further investigate the influence of conscious and unconscious perceptions of lighting on individual conflict behaviors that occur daily.

2.5.2 Healthcare spaces

Exposure to light can have positive and negative impacts on human health and should therefore be considered an environmental factor for prevention or specific applications. Lighting can be particularly effective in immediate healthcare areas such as doctors' offices, clinics, birth centers, and nursing facilities.

In short, light is electromagnetic radiation that, especially in the non-visible ultraviolet (UV; 100 nm – 400 nm) and infrared (IR; 780 nm – 10,000 nm) ranges, impacts physical health, especially the eyes and skin. Beyond the CIE (2020a) definition of integrative lighting or HCL, which excludes therapeutic treatments, light therapies are also an important area for the treatment of depression and sleep disorders. Given that this works focuses on light in the visible spectrum of 380 nm – 780 nm, aspects of UV and IR radiation only briefly reviewed.

UV radiation is necessary for humans to gain vitamin D, especially cholecalciferol (vitamin D_3) which regulates calcium uptake. In addition, vitamin D is thought to play a regulatory role in the immune system and aid in the prevention of cancer, diabetes, and hypertension (Holick, 2007; Webb & Engelsen, 2006) as well as psychological disorders such as depression, anxiety, and schizophrenia (Berk et al., 2009).

However, overexposure to UV radiation, whether from sunlight or electric light sources, is directly related to erythema and skin cancer (Freeman et al., 1970; Narayanan et al., 2010).

The potentially bio-destructive effect of UV radiation can also be actively used, for example, to purify air, liquids, and granular materials by deactivating pathogens such as fungal spores and bacilli (Brickner et al., 2003; S. L. Miller et al., 2013). The most effective wavelength range for bio-destructive effects is approximately 400 nm – 500 nm, which is also referred to as blue light hazard (Bullough et al., 2019).

Regarding care facilities, it is important to note that specific groups such as newborns and children are particularly sensitive to UV radiation. As such, none of the otherwise widely used LED lighting with a peak emission of 440 nm – 460 nm should be used in maternity units and pediatric facilities (Sanford et al., 1996; Zak & Ostrovsky, 2012). In addition, there are a large number of other groups in which photosensitive changes are present, for example, for such as, post-operative cataract patients, drug-affected or aphakic people (Boyce, 2014; Werner et al., 1990).

Radiation in the visible and non-visible (IR) wavelengths (400 nm – 1,400 nm) can damage the retina by increasing the temperature of the pigment epithelium, which is referred to as chorio-retinal damage (Boyce, 2014). In addition to this thermally induced damage, damage known as photoretinitis can also occur at lower radiation energy levels. High energy levels of IR radiation (> 1 W/cm2) can also cause thermal damage to the skin (Boyce, 2014).

The positive effect of exposure to light as radiation is also used in phototherapies for conditions such as hyperbilirubinemia (jaundice; Maisels & McDonagh, 2008; Stokowski, 2006); skin diseases such as psoriasis, eczema, and vitiligo (Bouceiro Mendes et al., 2022; Boyce, 2014; Kemény et al., 2019); and tumors (H. Shi & Sadler, 2020).

Unsteady lighting conditions can trigger headaches (Shepherd, 2010) and even epileptic seizures (Fisher et al., 2005; Harding & Jeavons, 1994). According to Harding and Jeavons (1994), humans are most sensitive to flicker in the frequency range between 15 – 50 Hz.

Due to their higher sensitivity to changes in the environment, autistic individuals may also benefit from low flicker rate lighting. Observations support that autistic individuals under flicker-free incandescent light instead of fluorescent light reduce repetitive behavior to regulate arousal (Colman et al., 1976; Fenton & Penney, 1985).

Exposure to bright light, usually between 2,500 lx and 10,000 lx, is used as an effective treatment for seasonal affective disorder (SAD; Baczynska & Price, 2013; Golden et al., 2005). In addition, light is also used in the context of Parkinson’s disease, Alzheimer's, and other forms of dementia, as well as in nursing homes in general to improve cognitive function (Hanford & Figueiro, 2013; Johnstone et al., 2015; Zou et al., 2022).

According to a literature review of Vetter et al. (2022) , there is no doubt that irregular light exposure can lead to circadian disturbances. These so-called circadian disruptions are considered as an risk factor for metabolic and cardiovascular diseases and have been associated with hormone-sensitives cancers and mortality in several studies (Abbott et al., 2020; S. T. Davis et al., 2001; Evans & Davidson, 2013; Karatsoreos et al., 2011; Lunn et al., 2017; Portnov et al., 2016). Endocrine disruption, especially of melatonin, also affects the immune system (Bedrosian et al., 2016; Dominoni et al., 2016; Russart & Nelson, 2018).

Effects of light at night time are associated with obesity and impaired glucose tolerance (Fonken & Nelson, 2014; Obayashi et al., 2013; Y.-M. M. Park et al., 2019; Vetter et al., 2022). For example, blue-enriched light exposure in the morning and evening acutely alters glucose metabolism via reduced insulin sensitivity (Cheung et al., 2016).

Improved lighting has significant benefits for humans. Pattison et al. (2018) and Vetter et al. (2022) conclude that while individual health benefits may be modest, population-wide benefits can lead to extensive overall health gains.

2.5.3 Residential spaces

Lighting in private interiors is a category of space that is difficult to describe in a generalized, internationally valid way. Within an apartment, there are various requirements for lighting scenarios. In kitchens and sanitary areas, for example, bright and high CCT lighting is more desirable for hygienic reasons, whereas living rooms and bedrooms are more suited to low CCT associated with warmth and relaxation (Baron et al., 1992; R. Chen et al., 2022; Hsieh et al., 2020; Kong, Liu, et al., 2022). Thus, depending on the specific function of the space, the requirements profile for lighting changes. Technical possibilities, meaning which technologies are available and which dynamic lighting conditions are possible to create, are also a determinant. Furthermore, climatic and cultural differences also have an influence on lighting preferences, such as lighting color quality (H. Lee & Lee, 2021; A. Liu et al.; X. Liu et al., 2015; Quellman & Boyce, 2002) and illuminance level (Belcher, 1985; Eissa, 2015) are assumed. Nonetheless, the demand for advanced lighting solutions, led by the European market with a USD 750 million share of global sales of USD 1 billion in 2020, is growing (Global Market Insights Inc., 2021).

Few studies have concretely evaluated appropriate lighting in private environments such as living rooms. These differences are evaluated according to "liveliness," which was described by Chinese in high CCT (5,500 K) lighting, while Dutch associated this with lower CCT (2,500 K). Thus, Liu et al. (2015, p. 581) concluded that higher CCT lighting “would make the room more lively for Chinese observers but less lively for Dutch observers". However, individual studies cannot provide a comprehensive explanation due to the complex cultural factors of lighting.

To investigate the various lighting situations in residential environments, neurophysiological studies have also been conducted, for example, on the effects of direct versus indirect lighting. A study using electroencephalography (EEG) by Shin et al. (2015) indicated that ambient lighting can significantly influence brain cortical activity and that EEG signals can serve as a biological marker of environmental alterations.

2.5.4 Industrial spaces

Industrial spaces are typically found in factories and are often characterized by windowless rooms with high ceilings. Lighting therefore has the primary function of ensuring sufficient brightness for work to take place. Shift work is also common in the industrial sector and is therefore an aspect to be considered with regard to HCL.

Despite the wide range of lighting options available to industrial lighting designers, the objectives of lighting are usually the same. Boyce (2014) defines three objectives for industrial lighting: (1) to facilitate quick and accurate work, (2) to contribute to the safety of workers, and (3) to create a comfortable visual environment.

With regard to the constant use of lighting equipment, this can be complemented by reliable, but also economically efficient installation, operation and maintenance.

High-mounted luminaires are used for high walls, but this can make shadows a problem. General recommendations for the right lighting are therefore difficult and depend on the respective task area and processed materials.

In a study with workers in a truck factory, Lowden et al. (2004) demonstrates that high illuminance lighting increased perceived alertness during the night shift. Also Juslen et al. (2007) showcases that increased illuminance levels during night shifts accelerate human repair performance on a packaging line in a chocolate factory. But brightness and comfortable lighting should be a balance which shows a study by Juslen (2005) in a windowless luminaires assembly hall. Workers could individually adjust the lighting level at their workstations between 270 lx and 3,300 lx. After two months, the average level settled at 1,405 lx and productivity increased by 4.5%. However, whether this increase was due to improved visual performance, alertness, mood, or a combination of these cannot be determined reliably.

In sum, modern industrial lighting must adequately consider functionality with regard to processes and materials as well as the needs of human workers.

2.5.5 Public and commercial spaces

Public and commercial spaces are spaces that are accessible to many people and where people meet and interact. Typical examples are urban squares; stores; conference centers; trade fairs; restaurants; hotels; and entertainment and cultural facilities such as sports venues, cinemas, theaters, stadiums, museums, and concert halls. All these buildings and areas use electric lighting and can therefore be reviewed from an HCL perspective.

Current research includes a variety of studies from the consumer perspective. For example, there are evaluations of lighting concepts in wine (Areni & Kim, 1994) and fashion stores (Custers et al., 2010; Hemalatha et al., 2022; Schielke & Leudesdorff, 2015), dressing rooms (Alsaleh et al., 2020), in restaurants (Bschaden et al., 2020; Özkul et al., 2020; Wu & Wang, 2015), and hotels (N.-K. Park et al., 2010; Yang, 2015). The evaluation of lighting design in retail areas is conducted in real stores with genuine consumers (Custers et al., 2010; Cuttle & Brandston, 1995), in supermarket settings built in laboratories (Quartier et al., 2014) or through computer-based visualizations (Yilmaz, 2018).

Highlighting merchandise has been shown to increase time spent in shops and exploration of items (Nell, 2017; Summers & Hebert, 2001). Additionally, higher illuminance levels and highlighting of products are associated with more purchases (Cuttle & Brandston, 1995). At the same time, studies have determined that products in a highly illuminated environment were generally rated as lower in quality than the same products displayed under dim lighting (Babin et al., 2004; Baker et al., 1992). Preferences also depend on the product itself and the product category, such as fresh food versus packaged products, as Horska and Bercik (2014) indicate.

However, these spaces should be considered not only from the perspective of the consumer or visitor but also from the point of view of the operator, who is interested in an economical lighting solution, as well as the employees who work in such spaces, such as salespersons (Denk et al., 2015). Especially with regard to energy efficiency and environmental sustainability, which many companies and public institutions strive for, there are numerous publications discussing the costs and benefits of new LED lighting solutions (Almeida et al., 2014; Chinchero et al., 2020; Gan et al., 2013).

In addition to commercial spaces, cultural meeting points such as concert halls and museums are examined for their lighting concepts. For example, Lo & Steemers (2020, 2022) develop approaches for measuring and improving the impression of concert lighting on visitors. Kesner (1993), Liu et al. (2019), and Cevik et al. (2022) address the evaluation of lighting concepts in museums. Places like museums have the peculiar need to achieve lighting that is optimal not only for visitors but also for the protection of exhibits. Inadequate lighting can cause lasting damage to paintings in particular, resulting in a European technical standard for indoor exhibitions of cultural heritage (DIN & European Committee for Standardization [CEN], 2014).

In the context of public spaces and urban design, the concept of "social lighting" has been discussed since the 1990s (Brandi, 2007; Entwistle & Slater, 2019; Narboni, 2004). According to Entwistle (2019), urban lighting concepts serve to illustrate how institutionalized distinctions – for example, between technology and aesthetics – can produce a sociologically impoverished space and must also be considered within a social context. In this manner, spaces can be differentiated according to safety or aesthetic aspects. Boyce (2014) addressed security aspects in a detailed review of lighting and crime. Security aspects of lighting are derived from studies dating back to a government project in the United States in the 1970s (Tien et al., 1979) to field experiments in UK (Painter, 1996; Painter & Farrington, 1999). The analysis of such studies is also accompanied by discussions regarding appropriate measurements, appropriate statistical procedures, and appropriate interpretations of results (Farrington & Welsh, 2006; Marchant, 2004).

Considering the wide range of studies and methodological discussions, it is reasonable to agree with Boyce's (2014, p. 484) conclusion that "lighting, *per se*, has no direct effect on crime. Rather, it has an indirect effect by facilitating surveillance, community confidence and social control."

In addition, lighting in pedestrian and road traffic areas is an active field of investigation into lighting's impact on traffic safety (Al-Haji, 2014; Fotios et al., 2015; Fotios & Goodman, 2012; Marchant et al., 2020; Ylinen et al., 2011). Research in this area is increasingly moving toward intelligent adaptive systems that integrate an HCL perspective (Ibrahim et al., 2020; C.-H. Liu et al., 2021; Siess et al., 2015).

2.5.6 Virtual spaces and Metaverse

Virtual illumination of virtual environments is used in virtual spaces such as 3D computer games, virtual meeting spaces, and Metaverse platforms as well as in simulations for research purposes. Illumination can be the simulation of daylight, an abstract illumination of interiors, or a realistic simulation of electric light sources with certain illuminances, light distributions, light reflections, shadows, and so on. Simulated lighting usually refers to the process of simulating the behavior of light in the real world using mathematical models and algorithms (Chokwitthaya et al., 2017; Guo & Pan, 2015). This type of lighting is used in architecture, rendering software to create photorealistic images or animations of objects and scenes, and laboratory environments (Inanici, 2004). Simulated lighting takes into account the physical properties of light, such as its intensity, color, direction, and how it interacts with different surfaces.

Virtual lighting, on the other hand, refers to the lighting that is specifically designed and used within a virtual environment or game (Duffy & Chan, 2002; Knez & Niedenthal, 2008). Virtual lighting can be created using various techniques, including simulated lighting, but it is also optimized for real-time performance, interactive applications and design purposes (Cui et al., 2022). In summary, simulated lighting is a general term that refers to the process of simulating the behavior of light, while virtual lighting is a more specific term that refers to the lighting used within a virtual environment.

Creating realistic lighting with natural-looking lighting effects has been the objective in video games for decades (Iones et al., 2003). Technical capabilities like head-mounted displays (HMDs) have facilitated the aim to design immersive virtual environments (IVEs).

Virtual spaces can be visited both via two-dimensional screens or via augmented or virtual reality devices. Opaque virtual reality (VR) glasses are generally more suitable for immersive applications and are particularly popular in the gaming context. The sales volume of augmented reality (AR) and VR devices is increasing rapidly. According to a study by market research agency TrendForce, sales of AR and VR headsets nearly doubled to 9.9 million units from 2020 to 2021. The market is forecasted to grow to 14.2 million units in 2022 and 18.1 million units in 2023 (TrendForce, 2022).

According to a study by PricewaterhouseCoopers (PwC), AR and VR were estimated to have increased the global Gross Domestic Product (GDP) by USD 46.5 billion in 2019. Moreover, PwC expect that AR and VR technology will contribute a GDP increase of USD 1.5 trillion and provide over 23 million new jobs by 2030 (PwC, 2019).

Regardless of whether these impressive forecasts are accurate, it must be assumed that many interactions in the coming years will take place in virtual environments.

In this context, virtual interaction can take place in closed platforms or in open systems. Open systems are also termed 'Metaverse' (Dionisio et al., 2013). The term Metaverse originated in a 1992 science fiction novel and described a colossal, spherical planet that users access through virtual reality technology (Stephenson, 1992). According to common understanding, "metaverse is a compound word of transcendence meta and universe and refers to a three-dimensional virtual world where avatars participate in political, economic, social and cultural activities" (S. Park & Kim, 2022, p. 4211). Park and Kim (2022) illustrate the challenge of finding a unified and consistent definition of the term in their analysis of 260 papers on understanding the metaverse, and they list 54 different definitions from scientific papers. The focus of a metaverse is not on the photorealistic reproduction of the physical environment but rather on the creative implementation of interaction possibilities; it is discussed as an new iteration of the internet (Dwivedi et al., 2022). The activities in a metaverse rely to augmented and virtual reality services and equipment (Damar, 2021).

The comparability and relationships between light impressions and presence in physical and virtual environments represent a broad area of research, especially in the last two decades (Mania, 2001; Mania & Robinson, 2004), and have been subject to systematic reviews (Bellazzi et al., 2022).

The following is a summary of key findings from contemporary studies:

(1) There seems to be no difference in the perception of physical and virtual spaces (Hong et al., 2019; X. Jin et al., 2022).

(2) The perceptions of lighting and impressions of a room are perceived equally in physical and virtual spaces (Abd-Alhamid et al., 2019).

(3) For task performance, such as reading a passage or counting books on a bookshelf, under light and dark lighting conditions, there are no performance differences in physical or virtual environments (Heydarian et al., 2015).

(3) In virtual spaces, large windows are associated with more brightness and are generally preferred (Abd-Alhamid et al., 2020; Moscoso et al., 2020, 2022).

(4) Subjects also prefer daylight in virtual environments (Heydarian et al., 2016; Heydarian et al., 2017; Mahmoudzadeh et al., 2021).

(5) Other sensory perceptions like thermal perception (Chinazzo et al., 2021; Salamone et al., 2020) and taste (Cornelio et al., 2022) can be affected by virtual lighting conditions.

Also studies gain knowledge on the effects of CCT and illuminance on visual perception and task performance in IVEs (Llinares et al., 2021; Ma et al., 2022), on spatial perception of ceiling height and type variation (S. H. Cha et al., 2019), and establish procedure for evaluating the impact of discrepancies between lighting simulations in IVEs and actual lighting conditions (Chokwitthaya et al., 2017).

With reference to lighting planning, virtual spaces are used in architectural, interior, and building design (Heydarian et al., 2017; Kalantari & Neo, 2020; Krupiński, 2020; Laffi, 2022; Scorpio et al., 2021). In film and theater, VR can provide immersive experiences and promote correct perceptions of depth and proportion to visualize spaces and lighting (L. Wang, 2022). Virtual spaces are also used to study and optimize consumer-oriented lighting in retail environments (Y.-F. Lin & Yoon, 2015; Quartier et al., 2014) and for urban planning (Scorpio et al., 2020). Especially for ambitious use cases in the metaverse, such as art exhibitions, the important role of simulated lighting in virtual spaces is also discussed in computer science (Cui et al., 2022).

However, despite these various use cases and the cost and time savings that result from research and lighting design, there are methodological and technical limitations to consider. After a systematic literature review of 33 studies on using VR to assess visual quality and lighting perception, Bellazzi et al. (2022) state that the primary limitation of VR for lighting research is the absence of a standardized investigation approach. Bellazzi et al. identify an opportunity to reduce limitations, facilitate the replication of results, and expand this field of investigation by defining diverse lighting goals.

Other inherent limitations are the technical capabilities of the devices used. For example, it can be assumed that a glare sensation cannot be reproduced like real daylight due to the lower luminous stimulus provided by HMDs. However, technical limitations can often be overcome by technological progress.

3. Lighting research methods

Ergonomic and psychophysical measurement methods have been used in lighting research since the 20th century and are still being developed today. For this purpose, questionnaires and instrument-based research methods are used (Khanh et al., 2022). Early lighting research focused on the relationship of lighting levels to work productivity and accident occurrence in industrial environments (Lindner, 1975).

Classification of lighting research

Today, lighting research can be classified by the mode of presentation of visual stimuli (Ma et al., 2022) and include the following types of studies.

(1) Field studies in specific spaces

Field studies are widely used to explore visual preferences (Chraibi et al., 2017; Sun et al., 2019; Veitch & Newsham, 2000) or non-visual effects like mood and task performance (Boyce et al., 2000; Hoffmann et al., 2008; Viola et al., 2008). Places of field studies can be offices (Kort & Smolders, 2010; Wei et al., 2014), factories (Juslén et al., 2005, 2007; Lowden et al., 2004), urban places like streets (Painter, 1996), concert halls (Lo & Steemers, 2022), retail stores (Cuttle & Brandston, 1995), classrooms (Bellia et al., 2013; Keis et al., 2014; Kong, Zhang, et al., 2022), or even private living spaces (Falkenberg et al., 2019). One advantage of field studies is the biotic environment and the authenticity of the lighting situations. However, an associated disadvantage is that light stimuli such as intensity, duration, spectral power distribution, or position relative to the eyes cannot be fully controlled. Relevant individual behaviors such as involuntary pupillary responses, movements between different locations, gaze behavior, and prior light exposure represent potential confounding variables (Vetter et al., 2022). The more biotic the study environment and the behavior of the subjects, the more difficult it is to control or isolate variables.

(2) Laboratory studies in physical spaces

A typical approach in psychological lighting research is to conduct research in a laboratory environment in which the lighting conditions to be studied are provided. Sometimes scenarios such as an office environment (Aries et al., 2020), conference rooms (Loe et al., 1994), retail stores (Denk et al., 2015), and even aircraft cabins (Winzen et al., 2014) are simulated under controlled conditions.

(3) Photo- and rendering-based studies

For illuminance and CCT studies, photo-based simulations of lighting settings are often used (Moscoso & Matusiak, 2018; Newsham et al., 2004; N.-K. Park et al., 2010). Renderings of lighting settings are also common for research on visual perception and the assessment of different lighting scenarios (Murdoch et al., 2015; Newsham et al., 2005; Villa & Labayrade, 2015). Three-dimensional miniature replicas of spaces with correspondingly altered lighting settings are rare but still used as well. For example, Ampenberger et al. (2017) used a 1:10 scale model of a store with different lighting settings to assess differences in perceived spatial brightness.

(4) IVE studies in virtual spaces

IVE studies are used to explore visual preferences (Heydarian et al., 2015) or non-visual effects like mood and task performance (Chokwitthaya et al., 2017; Ma et al., 2022). VR environments, especially for visual effects, are considered an equal alternative to experiments in physical environments. However, there are limitations, especially in terms of non-visual effects, as the perception and light distribution of an HMD is limited and not equivalent to actual lighting (Vetter et al., 2022).

Research instruments

Various instruments are used as measurement methods in light research, including (1) subjective assessments by questionnaires and interviews, (2) observations, and (3) physiological measures.

Kong et al.'s (2022) review of 64 studies demonstrates that all studies followed a similar protocol involving collecting subjective responses under predesigned lighting simulations. Studies investigating electric lighting (32 out of 40) used laboratory mock-ups or simulated rendering images (8 out of 40).

All the studies reviewed by Kong et al. (2022) utilize a survey questionnaire with self-report assessments to collect subjective responses. To capture affective meaning and attitudes, well-established methods like Likert-scale questions (Likert, 1932) and semantic differentials are used (Adams & Osgood, 1973; Osgood, 1962).

Mood and emotions are two distinct but related psychological constructs and are also addressed in lighting research. Mood is a pervasive and sustained affective state that colors a person's perception of the world and their experiences (Scherer, 2005). It is typically described as a subjective feeling that is not necessarily tied to a specific stimulus or event. Moods also are considered diffuse affect states characterized by a relatively enduring predominance of certain types of subjective feelings that affect a person's experience and behavior (Scherer, 2005). Moods can be positive (e.g., happy, content) or negative (e.g., sad, anxious) and can persist over hours, days, or even longer periods of time.

Following the definition of the American Psychological Association (APA), mood is defined as "any short-lived emotional state, usually of low intensity (e.g., a cheerful mood, an irritable mood)" (American Psychological Association [APA], 2023b) and as

> a disposition to respond emotionally in a particular way that may last for hours, days, or even weeks, perhaps at a low level and without the person knowing what prompted the state. Moods differ from emotions in lacking an object; for example, the emotion of anger can be aroused by an insult, but an angry mood may arise when one does not know what one is angry about or what elicited the anger. Disturbances in mood are characteristic of mood disorders. (APA, 2023b)

In contrast, emotions are brief and intense affective states that are typically triggered by specific events or stimuli (Scherer, 2005). They involve physiological responses, such as changes in heart rate, blood pressure, and facial expressions, and are often accompanied by subjective feelings and behaviors. Examples of emotions include anger, fear, joy, and sadness. Following the definition of APA emotion is

> a complex reaction pattern, involving experiential, behavioral, and physiological elements, by which an individual attempts to deal with a personally significant matter or event. The specific quality of the emotion (e.g., fear, shame) is determined by the specific significance of the event. For example, if the significance involves threat, fear is likely to be generated; if the significance involves disapproval from another, shame is likely to be generated. Emotion typically involves feeling but differs from feeling in having an overt or implicit engagement with the world. (APA, 2023a)

Both mood and emotions are important components of daily life and play a crucial role in social interactions, decision-making, and overall well-being.

Self-reports of recent emotional experiences are likely to be more valid than self-reports of emotions that occurred at some point in the past (Mauss & Robinson, 2009; Robinson & Clore, 2002). For the measurement of affective states, light studies often use measurement instruments that are already established in psychology, such as Self-Assesment Manikin (SAM), Positive Negative Affect Schedule (PANAS) and the Pleasure-Arousal-Dominance Model (PAD; Khanh et al., 2022; Mehrabian, 1995, 1996; Mehrabian & Russell, 1974). Only in rare cases is data collected via focus group interviews and naïve sketches (Nell, 2017).

Studies on lighting design in cities or the effect of lighting in stores also use statistical observations to determine, for example, changes in length of stay or path use. These studies typically do not require explicit information from individuals but rather focus on the behavior of a larger population of people.

Laboratory tests are particularly well suited for studies of the physiological effects of lighting. For example, the suppression of melatonin levels due to the influence of bright light is detectable in blood, saliva, and urine (Arendt, 2006; Lewy et al., 1980; Vetter et al., 2022; Zeitzer et al., 2000). Additionally, technologies such as EEG (Akerstedt et al., 2003; Cajochen et al., 2000; A.-M. Chang et al., 2013; Lowden et al., 2004; Min et al., 2013; L. Shi et al., 2009), electrocardiography (ECG; Askaripoor et al., 2018; Cajochen et al., 2005; Figueiro et al., 2009; Kuijsters et al., 2015; Kuller & Wetterberg, 1993), measurement of skin conductance level (SCL) via electrodermal activity (EDA; Caldwell & Jones, 1985; Huiberts et al., 2016, 2017; Smolders & Kort, 2017) and the record of body temperature (Badia et al., 1991; Cajochen et al., 2005; Heo et al., 2017; Kakooei et al., 2010; Prayag et al., 2019; Te Kulve et al., 2018) are used to determine physiological effects of lighting.

Challenges and developments

Phillips et al. (2019) demonstrate that the same dim evening light environment is registered differently between individuals; thus, interindividual variability may be an important factor in determining circadian effects. Factors of an interindividual variability may be like genetic polymorphisms and biological sex, as noted by Chellappa et al. (2014; 2017) and Roecklein et al. (2009). However, Kakitsuba (2020) perceptual study using ECG and EEG finds no sex differences in psychological and physiological responses to exposure to lighting at different illuminance (70 lx – 7,000 lx) and CCT levels (3,000 K; 4,000 K; 5,000 K). In addition, temporal relations can also be disruptive factors. Light exposure earlier in the day can lessen the melatonin rhythm phase delay caused by light exposure just before bedtime (A.-M. Chang et al., 2011; Hébert et al., 2002; Kozaki et al., 2015; Zeitzer et al., 2011). Due to the complexity of this research field, more studies are necessary to derive scientifically tenable conclusions about individual factors.

The physiological effects of light are well studied compared to psychological effects. Due to the high complexity of this research field and the multitude of study designs, methods, and procedures, there is a strong need for further research.

Tutorials (Kort, 2019) and technical notes (CIE, 2018, 2020b) recently provided guidance and defined which parameters should be documented, for example, in studies of ipRGC-influenced responses to light. Such guidelines lead to increasing professionalization and better comparability of studies within this interdisciplinary field of research.

4. Interim conclusion and research gaps

In summary, light research has undergone significant progress since its origins in the 20th century. Findings from architecture, business administration, engineering, ergonomics, medicine, physics, psychology, and so forth are brought together in this context. Early research focused on the relationship between lighting levels and productivity in industrial environments. Today, lighting research has expanded to cover various spaces and environments, including offices, factories, urban places, and even private living rooms.

Four categories of visual stimuli presentation in lighting research have been identified: field studies, laboratory studies, photo- and rendering-based studies, and IVE studies in virtual spaces. Various instruments are used as measurement methods in light research, including subjective assessments, observations, and physiological measures. However, research gaps remain in the field of lighting research, particularly regarding non-visual effects. To fully understand the effects of lighting on mood, emotion, and other non-visual effects, further research is needed, especially in physical and virtual environments where confounding variables can be controlled in different ways. Relying on the preceding literature-based exploration, two aspects emerged that are of particular interest in this work:

(1) The influence of lighting on social interactions such as negotiations and conflict handling.

There is little literature on conflict and negotiation management in different lighting situations (Baron, 1990; Baron et al., 1992; Kombeiz, 2016; Kombeiz et al., 2017; Kombeiz & Steidle, 2017; Steidle et al., 2013). Therefore, it is appropriate to critically examine the generalizability and transferability of the results through original experimental studies. This is an interesting area of inquiry, especially if the dependent variable can be assessed with Standardized procedures for assessing situational conflict styles, like the Thomas-Kilmann instrument (TKI). Based on previous psychological lighting research, it appears that, in addition to illuminance, color temperature is an important independent variable because it is relevant to everyday life. As indicated in the presented overview of lighting in specific spaces, different application contexts require different CCT conditions to achieve optimal lighting. Effects of lighting also be accompanied by people's implicit expectations for the lighting in certain contexts. Accordingly, studies of the non-visual influence of CCT in negotiation or conflict situations are an underrepresented topic that is highly relevant to people's everyday lives.

(2) Relevance of lighting in virtual spaces and transferability of findings and measurement methods from physical to virtual spaces.

The need to meet and work in remote locations during COVID-19 pandemic has led to an increase in virtual conferencing and has broadened discussion of metaverse applications. Current market figures and forecasts indicate that this is a multi-billion-dollar industry that will affect millions of users. Hence, there is a need to understand the impact of visual stimuli like lighting on the human experience in virtual spaces. However, the design of virtual environments, especially with respect to virtual lighting conditions, has not yet been adequately researched, and guidelines like those for physical lighting have not yet been developed.

The importance of lighting in virtual spaces lies in its ability to create visual effects such as a sense of space, depth, and atmosphere. The use of lighting in virtual environments can shape and emphasize architectural elements and create visual interest and contrast. However, non-visual effects can also be created based on subjective evaluation and emotions.

Certain findings from lighting research and measurement methods used in physical spaces may or may not be applicable in virtual environments due to differences in lighting technology, visual perception, and environmental factors. Thus, a question arises of whether people expect the same lighting settings in virtual spaces as in physical spaces. Likewise, it is worth investigating, for example, whether the color temperature of virtual lighting has similar visual and non-visual effects as in a physical environment. To investigate this, however, it is also necessary to have appropriate measurement methods for this purpose. It is therefore necessary to examine the methods used in physical light research for their transferability to virtual light research and to adapt them if required.

Following Boyce's (2016, p. 101) assertion that "[i]n many ways, human-centric lighting is new land waiting to be explored", human-centric lighting must be explored in application scenarios like virtual spaces. Ultimately, it must be determined whether the concept of human-centered lighting (HCL) can be extended to human-centered virtual lighting (HCVL) to improve the quality of stay in virtual spaces.

PART II EXPERIMENTAL STUDIES: EXPLORING EFFECTS OF CCT ON CONFLICT HANDLING STYLES AND IMPLICIT EXPECTATIONS

In the following chapters, specific gaps in research on light effects are identified and filled by the author's own experimental and literature-based research. Each chapter includes its own background, methodology and results. A general discussion and conclusion complete Part II.

5. Introduction

5.1 Background

In everyday life, there are a number of situations in which people face conflicting or incompatible needs, drives, desires, or demands. These interpersonal conflicts occur, for instance, when dealing with unreliable colleagues close to deadlines or negotiating with uncooperative landlords. People differ in how they deal with these conflicts. Various studies have suggested that environmental factors have effects on social behavior (Baron, 1990; Danielsson et al., 2015; Gifford, 1988; Hygge & Knez, 2001; Qingwei Chen & Taotao, 2018).

The influence of lighting conditions is considered a special factor influencing social behavior (Knez, 1995, 2001). Variable lighting conditions prevail in the majority of everyday situations. Lighting can also differ significantly depending on the environment, such as the workplace or home. Developments in lighting technology have generated research interests in visual perception, with evolving findings based on environmental and perceptual psychology regarding the influence of lighting conditions on human beings. The influence of color temperature and variations of warm white and cold white lighting on human psychology has been investigated for decades (Baron et al., 1992; Boray et al., 1989; Knez, 1995; Knez & Kers, 2000).

The optimization of lighting conditions in educational facilities is an active area of research (Al-Ayash et al., 2016; Aries et al., 2020; Baeza Moyano et al., 2020; Bellia et al., 2015; Kombeiz & Steidle, 2018; Pulay & Williamson, 2019). Moreover, research in private and commercial areas has also shown interest in the benefits of lighting (Alsaleh et al., 2020; Areni & Kim, 1994; Baek et al., 2018; Denk et al., 2015; Entwistle & Slater, 2019; Kakitsuba, 2020; Y.-F. Lin & Yoon, 2015; N.-K. Park et al., 2010; N.-K. Park & Farr, 2007; Quartier et al., 2014). Scientific research in the workplace has likewise increased (Bluyssen et al., 2011; Boyce et al., 2006; Chraibi et al., 2016; Despenic et al., 2017; Figueiro & Rea, 2016; Hawes et al., 2012; Hoffmann et al., 2008; Khademagha et al., 2016; Knez & Enmarker, 1998; Kort & Smolders, 2010; Kraneburg et al., 2017; Mills et al., 2007; Tonello et al., 2019; Wei et al., 2014).

These various perspectives necessitate an interdisciplinary research approach that incorporates psychology, environmental research, architecture, and ergonomics to improve people's productivity, well-being, and efficiency by matching the environmental conditions to those correlated with enhanced cognitive performance. Indeed, the effect of lighting on cognitive performance has been supported by neuroscientific studies (Chellappa, Gordijn, & Cajochen, 2011; Chellappa, Steiner, et al., 2011; Lehrl et al., 2007; Vandewalle et al., 2009). Since lighting is part of everyday life, it can be adapted to meet specific needs.

Recent studies have indicated that electric lighting can inhibit or stimulate self-regulatory (Kang et al., 2019) and cooperative behavior (Kombeiz et al., 2017; Steidle et al., 2013).

Yet studies have seldom directly dealt with the influence of lighting parameters on self-regulation, cooperation, and negotiation behavior, indicating the need for further research (Baron et al., 1992; Kombeiz et al., 2017). While Baron et al. (1992) report inconsistent results, Kombeiz et al. (2017) observe that dim warm lighting activates interdependent self-construal and promotes collaborative conflict styles. It is therefore beneficial to further investigate the influence of conscious and unconscious perceptions of lighting on individual everyday conflict behaviors.

5.2 Implicit expectations and conceptual lighting

Humans are able to recognize regularities in the environment through an unconscious process called implicit learning. Experiments have determined that implicit learning influences how one processes and interacts with visual stimuli. Regularities in the environment have an important effect on perception. Terms used to describe the process that leads to implicit knowledge of environmental regularities include prior knowledge (Gerardin et al., 2010; Mamassian & Goutcher, 2001; Zhao et al., 2013) and statistical learning (Turk-Browne et al., 2010). Even kindergarten children recognize regularities in the lighting of different situations and report corresponding preferences (Vásquez et al., 2019).

Initial researchers have investigated implicit knowledge of lighting and its effect on the 3D reconstruction of our environment (Kersten et al., 2004). Zang et al. (2020) note that ambient lighting shifts throughout the day and leads to contextual learning effects that have not been systematically examined.

For decades, cold white light sources have been used in work environments such as factories, offices, and even classrooms, whereas private spaces favor warm white light sources. Workplaces generally use cold lighting to enhance performance (van Duijnhoven et al., 2019) while residential and social spaces use warm lighting to encourage relaxation and social interaction (Biner et al., 1989; Butler & Biner, 1987; E. Lee et al., 2013). The lighting conventions for fluorescent (work) and incandescent (home) lighting have been adapted to modern LED lights for work (cooler LEDs) and residential (warmer LEDs) spaces. Since these conventions are a regularity in the everyday environment, it can be assumed that people's visual system has paired cold lighting for work-related spaces and warm lighting for private spaces via implicit learning.

In addition to the warm and cold lighting conditions utilized in the following studies, the relationship between the presented lighting parameters and expectations for room lighting are defined in terms of congruent and incongruent conceptual lighting. In this thesis, the term "conceptual lighting" is used to describe implicit expectations about lighting for a given environment. While explicit knowledge can be tested directly with appropriate questions, indirect measures need to be devised to test implicit knowledge. In visual perception research, congruent and incongruent stimuli are used to investigate mental processes that function beyond conscious awareness. In congruent conditions, two mental concepts facilitate and cooperate with each other; in incongruent conditions, the two compete with each other. A comparison between congruent and incongruent conditions is used to infer aspects of implicit mental processing (Ghose & Palmer, 2010). In this study, "congruent conceptual lighting" is defined as the condition where physical lighting parameters match the implicit expectations of lighting for that space, whereas in "incongruent conceptual lighting," there is a mismatch due to experimental design. Thus, congruent conceptual lighting for work-related environments would be cold light, while for residential environments it would be warm light due to the repeated exposure of these combinations in daily life. This implicit association of different light sources with work-related and residential environments, along with physical color temperature, is an interesting psychological aspect of lighting that warrants further research.

5.3 Conflict handling

Systematic consideration of conflict resolution initially focused on a bipolar axis of cooperativeness and uncooperativeness (Deutsch, 1973). This approach was later expanded to include concrete strategies that make it possible to describe self-interests more clearly (Blake & Mouton, 1964; Thomas & Kilmann, 1978). The study of interpersonal behavior, such as conflict behavior, has since become an active field of research. Standardized questionnaires such as the Thomas-Kilmann Instrument (TKI) are used both in science and practice to record conflict behavior (Brahnam et al., 2005; Gbadamosi et al., 2014; Thomas, 1992; Volkema & Bergmann, 1995; Womack, 1988; Zhenzhong, 2006). The approach is based on the work of Blake and Mouton (1964) and assumes that individuals choose different style of conflict management. The TKI is also used in the widely cited lighting studies of Baron et al. (1992). According to the dual-concern model of conflict handling behavior (Thomas, 1992), a person's behavior in a conflict situation can be described in terms of assertiveness and cooperativeness. The TKI assesses an individual's behavior in conflict situations for five conflict handling styles, namely competing (high concern for self, low concern for others), collaborating (high concern for self and others), compromising (moderate concern for self and for others), avoiding (low concern for self and low concern for others), and accommodating (low concern for self and high concern for others).

Since conflicts are often emotionally charged situations, in the socio-psychological context, conflict handling as well as visual perception studies are accompanied by self-disclosure of emotional states, as recorded using instruments such as the SAM test (Bradley & Lang, 1994; Gatti et al., 2018; Shin et al., 2015; Wilms & Oberfeld, 2018; Wu & Wang, 2015). Lighting affects people's non-visual perception and emotions, and recent studies support that electric lighting can inhibit or stimulate self-regulatory (Kang et al., 2019) and cooperative behavior (Kombeiz et al., 2017; Kombeiz & Steidle, 2017; Steidle et al., 2013). Since conflicts can occur in environments with different lighting, there is a need to investigate whether indoor lighting directly influences conflict handling styles in everyday conflict situations.

5.4 Overview of the present research

The current research performs two separate studies to determine whether subtle (Study Conflict Handling 1 [CH1]) and noticeable (Study Conflict Handling 2 [CH2]) differences in color temperature of room lighting affect conflict handling styles, as measured by the TKI.

The consolidated research question is whether or not the color temperature of electric lighting affects conflict handling behavior.

The first study explored whether a subtle difference (ΔCCT = 1,300 K) in color temperature, which are realistic in an office or home environment, has an impact on conflict handling behavior and associated emotional levels. This study was conducted in a controlled laboratory condition with two different conflict scenarios (home and work) were presented as text descriptions in two different lighting conditions (warm and cold). Participants were asked to imagine themselves in those conflict scenarios and feel the associated emotions before filling in an online questionnaire using TKI and self-reporting of perceived emotions. Conflict handling behavior was measured according to the five TKI styles, namely competing, collaborating, compromising, avoiding, and accommodating.

In the second study, conflict handling style and associated emotions were measured in a controlled environment with noticeable differences (ΔCCT = 11,400 K) in color temperature but with the same lighting intensity (450 lx) as in Study CH1. The goal of Study CH2 was to investigate the effects of a more immersive lighting condition on avoidance and other TKI dimensions. Moreover, Study CH2 consisted of an additional questionnaire investigating whether participants indeed have different lighting preferences for different occasions. Since working locations often use fluorescent tubes with neutral and cold color temperatures, it can be assumed that conceptual lighting for working spaces is characterized by cooler color temperature than private spaces. Accordingly, conceptual lighting for living rooms compared to work rooms is warmer because there primarily incandescent lamps with lower CCT are used.

6. Study 1 (CH1): Effects of 1,300 K difference in CCT on conflict handling styles in private and work-related settings

6.1 Hypotheses

Based on the achievements of Chapter 5, the objective of this laboratory study was to investigate whether a subtle change in the color temperature (ΔCCT = 1,300 K) of room lighting can affect conflict handling styles in everyday conflict scenarios. This leads to a consolidated research question: Does the color temperature of the electric lighting affect the conflict behavior? This first Study CH1 explores whether marginal changes of the color temperature, within a range, possible in an office environment or in a living room, has an impact on the conflict handling behavior and associated emotional levels. To examine the superordinate hypothesis "H1: A subtle difference (ΔCCT = 1,300 K) in color temperature of the illumination affects the conflict behavior of individual", H1 has been divided into five conflict style indicators which result from the used measuring instrument for conflict handling, the Thomas-Kilmann-Instrument. For instance, "H1a: A subtle difference (ΔCCT = 1,300 K) in color temperature of the illumination affects the level of competing conflict style". To investigate each of the five conflict styles - competing (H1a), collaborating (H1b), compromising (H1c), avoiding (H1d), and accommodating (H1e) - they have been divided into sub-hypotheses (H1a – H1e) for testing.

6.2 Participants

The experiment was conducted with 68 participants (55 males, 13 females; M = 25.16 years, SD = 2.60 years) to achieve four groups of equal size. The participants were students at a German university who volunteered to participate for partial course credit in a graduate/undergraduate psychology course. They were naïve to the purpose of the experiment. All participants had normal or corrected-to-normal vision and were checked for normal color vision.

The participants provided informed consent in accordance with the policies of the University Committee for the Protection of Human Subjects. The experimental protocol was reviewed and approved by the ethics committee of the university. All participants were briefed about the purpose of the study after completion of the experiment.

To determine an adequate sample size, an analysis of comparable studies was carried out. Other laboratory studies investigating the psychological effects of the lighting environment feature sample sizes of 18 – 49 (Al-Ayash et al., 2016; Burattini et al., 2019; Kakitsuba, 2020; Kuijsters et al., 2015; C. W. Lee & Kim, 2020; Mao et al., 2018; Plitnick et al., 2010; Smolders & Kort, 2017; Steidle & Werth, 2014; Vries et al., 2018; Q. Wang et al., 2017), 50 – 79 (Knez, 1995; Knez & Enmarker, 1998; Kopcsó & Láng, 2019; Sleegers et al., 2013; Smolders et al., 2012; Steidle & Werth, 2014; Zhu et al., 2019), or more than 80 participants (Kombeiz et al., 2017; Kombeiz & Steidle, 2018). Given the wide variation in sample sizes, an a priori F-test power analysis in G*Power version 3.1.9.7 (Faul et al., 2007) was used with effect size $f = 0.35$. The power analysis indicated that 67 participants would yield 80% power. However, it is difficult to compare effect sizes across different sub-disciplines in psychology (Schäfer & Schwarz, 2019), so the most relevant past study (Steidle & Werth, 2014) was used as a benchmark for the number of participants.

6.3 Measures

The primary research question measured the conflict handling style of participants using the TKI. The TKI assesses an individual's behavior in conflict situations and comprises of 30 pairs of statements, with each pair of statements specifically designed to be equivalent in terms of social desirability (Jones, 1976; Kilmann, 2018). For each pair of statements, the respondent can choose "A" or "B" depending on which best matches their most likely behavior. These 30 dichotomous items reflect a preference for one conflict handling style among competing (assertive and uncooperative), collaborating (assertive and cooperative), compromising (moderately assertive and cooperative), avoiding (unassertive and uncooperative), or accommodating (unassertive and cooperative). TKI test scores are calculated using a standardized scheme in which the five conflict modes are represented in five columns each. For each conflict handling mode, there is a range of scores from zero (low usage) to 12 (high usage), and each score denotes the frequency of the selection of a TKI statement for that conflict mode (M. H. Davis et al., 2004).

Additionally, participants reported their levels of motivation, creativity, comfort, happiness, and anxiousness in a given lighting condition. A bipolar 5-point semantic differential scale with values ranging from –2 (i.e., indicating low motivation) to +2 (i.e., indicating high motivation; 0 = neutral) was used for each affect label. The scale provided insight into participants' emotional states under the given lighting conditions (Houser & Tiller, 2003; Wu & Wang, 2015). Due to the standardized procedure in Likert scales, potential outliers are not assumed to be due to measurement errors or data entry errors. Therefore, no data sets were removed from the analysis or post-processed by winsorizing or trimming.

6.4 Setting and procedure

The study was conducted on a 14-inch Dell LCD notebook (screen size 31 cm x 17.5 cm) with 1280 x 800 pixel resolution, screen brightness 250 cd/m^2, sRGB color space, and refresh rate of 60 Hz. It was placed on an office table in a 12.5 m^2 room with black walls and ceiling and windows covered with blinds and black curtains. The study was conducted without any daylight to avoid confounding variables. The light source was dimmable fluorescent ceiling lighting (4x Osram L18W 840) the color temperature of which could be changed by a filter foil (LEE 204 Full CTO) from approximately 3,800 K (x = 0.391, y = 0.392, CRI [R_a] = 83) to approximately 2,500 K (x = 0.487, y = 0.436, CRI [R_a] = 84).

After entering the experimentation room, the participants positioned themselves on a chair in front of the laptop. The laptop screen provided the description of one of the two pre-selected conflict related situations followed by an online survey. The participants were instructed to imagine themselves as really experiencing the presented conflict and to feel the associated feelings. No second person was employed as an interactive conflict opponent to prevent uncontrollable interaction effects. Participants completed the online survey with 30 questions from the TKI, along with additional 5-point-scale items related to perceived changes in their levels of motivation, creativity, comfort, happiness, and anxiousness.

The design of the two conflict situations was based on daily-life scenarios familiar to the student population:

(1) Landlord case: negotiating a disagreement with their landlord over a leaky faucet

> The washbasin in your student apartment is leaking. As soon as you unscrew the water tap, water runs onto your bathroom floor. You call your landlord for getting the tap repaired. Although you are sure that your landlord is responsible for these expensive repairs, he tells you that this is your problem and that you have to get it repaired at your own cost. You feel you are being treated unfairly in this situation. Your landlord refuses to listen to your arguments for tenant rights.

(2) Student case: negotiating with an uncooperative fellow student as the deadline of a joint presentation approached

> You have to prepare a presentation with a fellow student with whom you have never worked before. The same grade will be assigned to all group members. You agreed that each of you will prepare your own part until the day before the presentation and then you will meet only to discuss the details of the content you have prepared. However, your fellow student did not stick to this agreement. On the day of the meeting your fellow student calls you and informs you that the task is incomplete. You feel frustrated and unfairly treated in this situation.

The study was a mixed factorial design with conflict case (landlord, student) and lighting condition (warm, cold) as variables. The participants were divided in four equally sized subgroups referred to as “cohorts” based on the combination of lighting condition and conflict case, arranged in counterbalanced order, see Table 2.

Table 2

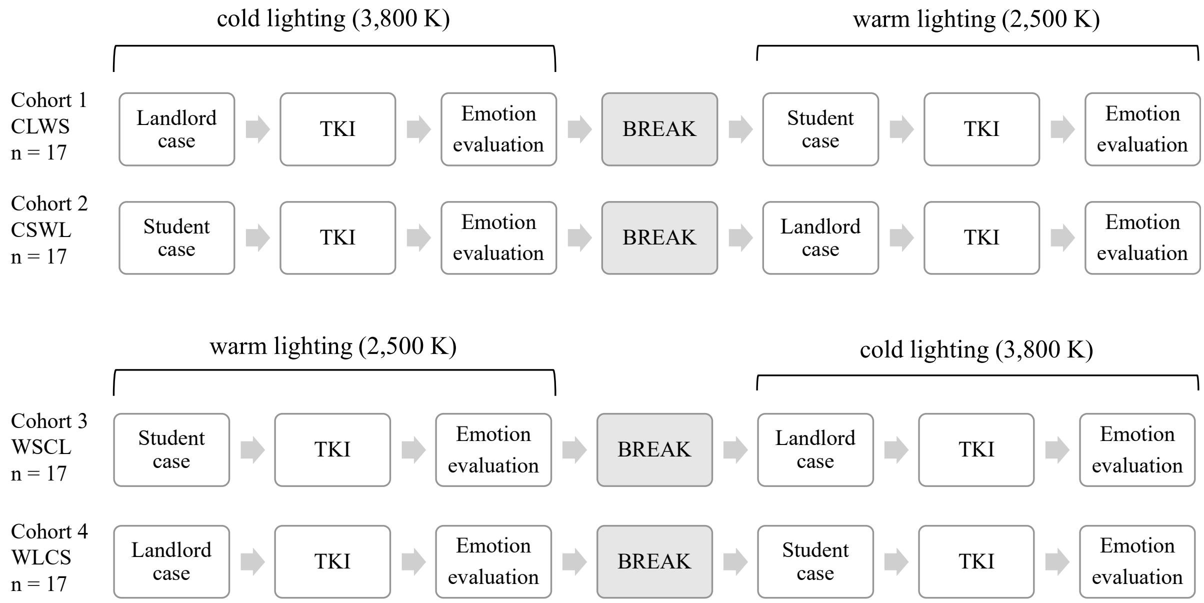
Composition of cohorts CH1

	Block 1		Block 2	
Test Group	Light condition	Conflict case	Light condition	Conflict case
Cohort 1 (CLWS)	Cold (C)	Landlord (L)	Warm (W)	Student (S)
Cohort 2 (CSWL)	Cold (C)	Student (S)	Warm (W)	Landlord (L)
Cohort 3 (WSCL)	Warm (W)	Student (S)	Cold (C)	Landlord (L)
Cohort 4 (WLCS)	Warm (W)	Landlord (L)	Cold (C)	Student (S)

The mixed factorial design enabled both between-subject and within-subject analysis (Fig. 6). The total duration of the experiment was reported as approximately 1.5 hours consisting of two 40-minute sessions separated by a 10-minute break. The illuminance level remained constant at approximately 450 lux, and the procedure of the second session resembled the first session. During the break, the participant was instructed to sit outside the experimentation room on a couch in the lobby. Meanwhile, the color temperature of the test room light was changed by the experimenter from warm to cold or vice versa, without the knowledge of the participant. At the end of the break, the participant was guided back into the experimentation room for the second session. After the second block, the participants were asked if they perceived any changes in the lighting conditions between the two blocks and to report if this change affected their emotional states.

Figure 6

Procedure Study CH1



Note. $N = 68$; C = cold lighting; W = warm lighting; S = student case; L = landlord case.

6.5 Results

6.5.1 Emotional states

Since it was difficult to make conformational statements with the available data, this analysis can best be described as exploratory. The five queries on the current emotion were evaluated with a paired *t*-tests. The five queries on current emotions were evaluated with a paired *t*-test. There were no significant differences in intrapersonal levels of motivation, $t(67) = -0.656$, $p > .514$, $d_z = 0.07$, creativity, $t(67) = 0.364$, $p = .717$, $d_z = 0.04$, comfort, $t(67) = 0.804$, $p = .424$, $d_z = 0.09$, happiness, $t(67) = 0.508$, $p = .613$, $d_z = 0.06$, and anxiousness, $t(67) = 0.450$, $p = .654$, $d_z = 0.05$, between the subtle warm and cold lighting used in Study CH1 (see Tables A8, A9).

6.5.2 Conflict handling style (TKI)

This study explored whether subtle changes in color temperature within the range possible in an office or a residential environment had an impact on conflict handling behavior and associated emotional levels. A descriptive overview of the TKI results can be found in Table 3, followed by a detailed analysis of each conflict handling style.

Table 3

Descriptive statistics of all group combinations in student cases with respect to the metric target variable of each conflict handling style CH1

	Student case				Landlord case			
	Warm		Cold		Warm		Cold	
TKI style	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Competing	4.97	2.79	4.97	3.65	5.35	3.75	4.15	2.57
Collaboration	5.88	1.79	6.38	2.15	6.38	1.94	5.74	1.96
Compromising	8.00	1.86	7.38	2.20	7.76	1.94	8.00	1.91
Avoiding	7.09	1.87	6.41	1.91	5.91	1.99	7.32	1.68
Accommodating	4.21	2.36	5.12	3.21	4.82	3.39	4.97	2.22

Note. $N = 68$.

There was no significant effect of lighting condition on conflict handling style (see Table 4), but multiple interaction effects are described below.

Table 4

Summary effects of TKI styles of warm versus cold lighting CH1

TKI style	*SS*	*df*	*MS*	*F*	*p*
Competing	12.360	1	12.360	1.189	.278
Collaborating	0.184	1	0.184	0.048	.827
Compromising	1.243	1	1.243	0.331	.566
Avoiding	4.596	1	4.596	1.292	.258
Accommodating	9.529	1	9.529	1.395	.240

Note. $N = 68$.

To determine the impact of lighting conditions on the distinct attributes of the five conflict styles – competing, collaboration, compromising, avoiding, and accommodating – a general linear model was used. The lighting conditions (warm or cold lighting), conflict case (landlord or student conflict), and block position (before or after the intermission) were used as between-subject factors. This served to identify interaction effects of the different conflict cases and block positions. In addition to this, a paired *t*-test was used to investigate the effects of light condition within the subjects on the respective conflict style.

Competing

The between-subject comparison (see Tables A1, A2) revealed the main and interaction effects of the intermediate subject factors without significant effects at $p < .05$.

Differences between the groups in terms of descriptive statistics and mean values cannot be confirmed. The mean values of a competing style did not differ in different lighting conditions, $F(1, 128) = 1.189$, $p = .278$, $\eta_p^2 = .009$. The paired *t*-test also showed no significant influence on the competing style in a within-subject analysis, $t(67) = 1.478$, $p = .144$, $d_z = 0.18$. The null hypothesis H1a must be retained.

Collaborating

When examining collaborating style (see Table A3), no statistical differences between the different lighting conditions were identified, $F(1, 128) = 0.048$, $p = .827$, $\eta_p^2 < .001$. The paired t-test also indicated no significant influence on collaboration in a within-subject analysis, $t(67) = 0.307$, $p = .759$, $d_z = 0.04$. The null hypothesis H1b must be retained.

Compromising

In compromising conflict style, the average score was 1.015 points higher, $F(1, 128) = 9.333$, $p = .003$, $\eta_p^2 = .068$, for the second conflict case (see Tables 5 and A4). However, there was neither a significant main effect of lighting, $F(1, 218) = 0.331$, $p = .566$, $\eta_p^2 = .003$, or interaction between lighting and block position, $F(1, 128) = 0.237$, $p = .627$, $\eta_p^2 = .002$). The paired *t*-test also showed no significant influence on compromising style in a within-subject analysis, $t(67) = 0.687$, $p = .494$, $d_z = -0.08$. The null hypothesis H1c must be retained.

Table 5

Block main effect for compromising CH1

Block	*M*	*SE*	*95% CI*	
			LL	*UL*
1	7.279	0.235	6.815	7.744
2	8.294	0.235	7.829	8.759

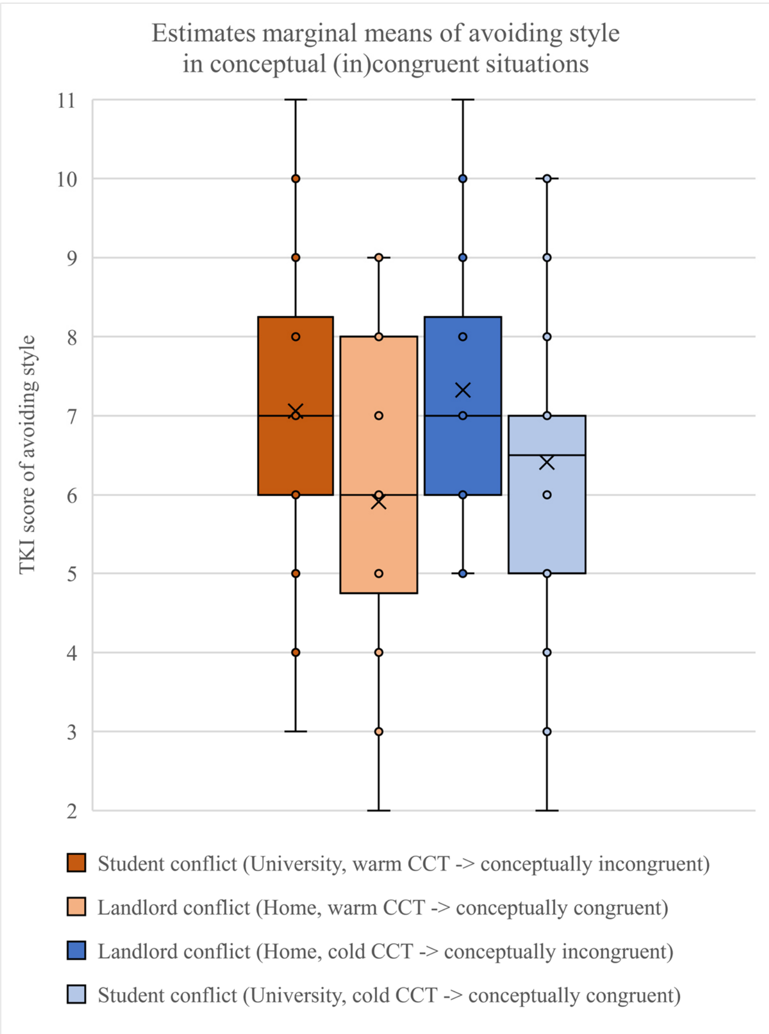
Note. $N = 68$.

Avoiding

The avoiding style reflected a significant interaction effect between lighting conditions and conflict case, $F(1, 128) = 10.421$, $p = .002$, $\eta_p^2 = .075$. Processing of the student of the student conflict under warm lighting ($M = 7.088$, $SD = 1.87$) showed a higher mean value for avoiding style than the processing of the landlord case (*M* = 5.912, *SD* = 1.99). The treatment of the student conflict under cold white lighting (*M* = 6.412, *SD* = 1.91) presented a significantly lower mean value for avoiding style than in the landlord conflict (*M* = 7.324, *SD* = 1.68), see Figure 7. Conceptually incongruent lighting accompanied increased avoidance.

Figure 7

Estimated marginal means of avoiding style CH1

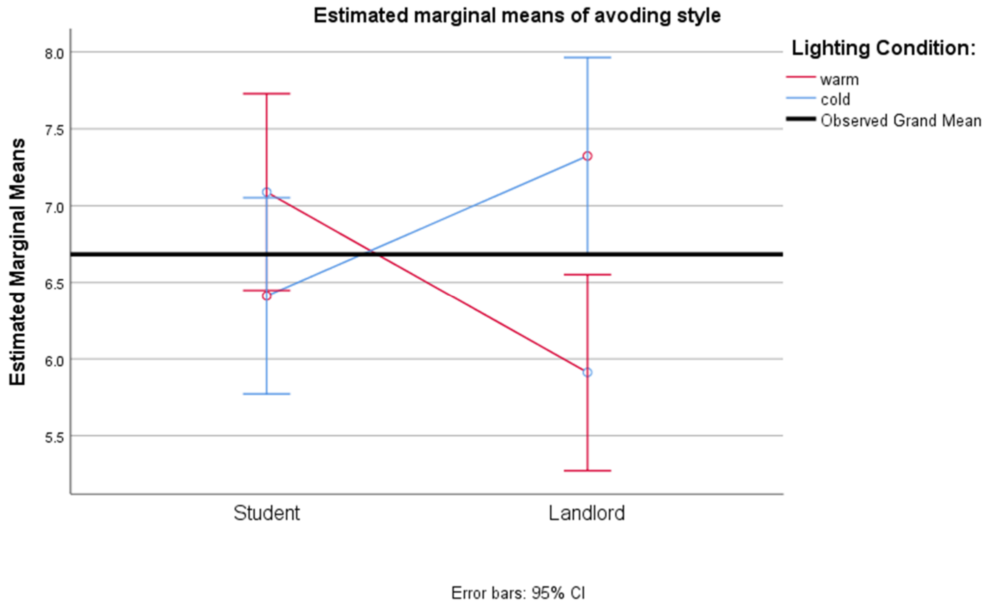


Note. $N = 68$.

An interaction effect (see Fig. 8, Table A5) emerged as soon as the lighting situation was no longer congruent with the setting of the conflict situation.

Figure 8

Interaction effect of avoiding style in incongruent lighting conditions CH1



Note. $N = 68$.

However, the between-subject analysis (see Table 6) did not reveal a general influence of lighting conditions on avoidance style, $F(1, 128) = 1.292$, $p = .258$, $\eta_p^2 = .010$. The paired *t*-test also showed no significant influence on avoiding style in a within-subject analysis, $t(67) = -1.637$, $p = .106$, $d_z = -0.20$. The null hypothesis H1d must be retained.

Table 6

Tests of between-subjects effects for avoiding CH1

Source	*SS*	*df*	*MS*	*F*	*p*
LightingCondition	4.596	1	4.596	1.292	.258
Case	0.596	1	0.596	0.167	.683
LightingCondition × Case	37.066	1	37.066	10.421	.002**
Block	0.890	1	0.890	0.250	.618
LightingCondition × Block	1.654	1	1.654	0.465	.496
Case × Block	1.243	1	1.243	0.349	.556
LightingCondition × Case × Block	0.066	1	0.066	0.019	.892

*Note. N = 68; * p* < .05, ** *p* < .01.

Accommodating

The analysis of accommodating style showed no significant effect from lighting condition, $F(1, 128) = 1.395$, $p = .240$, $\eta_p^2 = .011$, but did present two interaction effects (see Tables 7, A6, and A7). Firstly, there was an effect of block position, $F(1, 128) = 20.502$, $p = .001$, $\eta_p^2 = .138$. The extent of accommodating style was reduced in the second block ($M = 3.765$, $SD = 2.62$), compared to the first block ($M = 5.794$, $SD = 2.68$). Secondly, there was an interaction effect between the lighting condition and block position, $F(1, 128) = 4.978$, $p = .027$, $\eta_p^2 = .037$. In block 1, the accommodating value for the warm lighting condition ($M = 6.029$, $SD = 2.75$) was higher than for cold condition ($M = 5.559$ $SD = 2.63$). In block 2, the average value in warm lighting ($M = 3.000$, $SD = 2.23$) was lower than that in cold lighting ($M = 4.529$, $SD = 2.79$). The paired t-test yielded no significant influence on accommodating style in a within-subject analysis, $t(67) = -1.284$, $p = .204$, $d_z = -0.15$. The null hypothesis H1e must be retained.

Table 7

Tests of between-subjects effects for accommodating CH1

Source	*SS*	*df*	*MS*	*F*	*p*
LightingCondition	9.529	1	9.529	1.395	.240
Case	1.882	1	1.882	0.276	.601
LightingCondition × Case	4.971	1	4.971	0.728	.395
Block	140.029	1	140.029	20.502	.000**
LightingCondition × Block	34.000	1	34.000	4.978	.027*
Case × Block	11.765	1	11.765	1.723	.192
LightingCondition × Case × Block	4.971	1	4.971	0.728	.395

Note. $N = 68$; * $p < .05$, ** $p < .01$.

Regarding the independent variable of the lighting situation to be investigated, no direct and significant influence on the respective manifestations of conflict management styles can be confirmed. The results do not support the hypothesis H1 that lighting conditions have an influence on current conflict management behavior.

7. Study 2 (CH2): Effects of 11,400 K difference in CCT on conflict handling styles in private and work-related settings

7.1 Hypotheses

Based on Chapter 5 and Study CH1, the aim of this study was to investigate whether a noticeable change in the color temperature (ΔCCT = 11,400 K) of room lighting can affect conflict handling styles for the conflict scenarios. In contrast to Study CH1, the difference between reddish-white (1,600 K) and bluish-white (13,000 K) lighting was obvious upon entering the room. The results of the first study have been cross-checked with a clear difference in color temperature, but with the same light intensity (450 lx). H1 in Study CH2 therefore has been modified as follows: “H1: A significant difference (ΔCCT = 11,400 K) in color temperature of the illumination affects the conflict style.”. The corresponding sub-hypotheses relating the five styles remain similar to Study CH1 with the previously stated higher CCT difference value (H1a-H1e).

7.2 Participants

In order to be comparable, the sample size and cohort sizes of this study were matched to Study CH1. A total of 68 students (33 males, 35 females, $M = 25.16$ years, $SD = 2.50$ years) participated in this experiment. The participants were students at a German university. They volunteered to participate for partial course credit in a graduate/undergraduate psychology course. They were naïve to the purpose of the experiment. All participants had normal or corrected-to-normal vision and were checked for normal color vision. The participants provided informed consent in accordance with the policies of the University Committee for the Protection of Human Subjects. The experimental protocol was reviewed and approved by the ethics committee of the university. All participants were briefed about the purpose of the study after the experiment’s completion.

Since there is a wide variation in sample sizes in the previous study CH1 a priori F-test power analysis was used with effect size $f = 0.35$ in G*Power version 3.1.9.7 (Faul et al., 2007). The power analysis indicated that 67 participants would yield 80% power. To maximize comparability to the previous study CH1, which was conducted with 68 subjects, 68 subjects were recruited for this study as well.

7.3 Measures

Since the primary focus of this research was to measure participants’ conflict handling style, the TKI was used in the same way as in Study CH1. Similar to Study CH1, a bipolar 5-

point semantic differential scale with values ranging from -2 (i.e., demotivated) to +2 (i.e., motivated; 0 =neutral) was used for each of the following affect labels: motivation, creativity, comfort, happiness, and anxiousness. Due to the standardized procedure of Likert scales, potential outliers are not assumed to be due to measurement errors or data entry errors. Thus, no data sets were removed from the analysis or post-processed by winsorizing or trimming.

Additionally, self-disclosure of emotional states was recorded with the SAM test (Bradley & Lang, 1994; Gatti et al., 2018; Wilms & Oberfeld, 2018; Wu & Wang, 2015). SAM is a useful tool for accurately measuring emotional responses, as it is independent of language and provides a visual representation of participants' emotional states (Bradley & Lang, 1994; Geethanjali et al., 2017; Wilms & Oberfeld, 2018).

Table 8 depicts the three dimensions of SAM – valence, arousal, and dominance – with each dimension illustrated with five images representing values of 0, 25, 50, 75, and 100. The participants self-evaluated their emotions by using a slider for each of the three dimensions. The starting position of the slider was neutral (50).

Table 8

SAM ratings

Corresponding slider value	Valence rating	Arousal rating	Dominance rating
0	Pleasant	Excited	Dependent
25	Pleased	Wide-awake	Powerlessness
50	Neutral	Neutral	Neutral
75	Unsatisfied	Dull	Powerful
100	Unpleasant	Calm	Independent

Note. Adapted from Geethanjali et al., 2017.

Personal lighting preferences for different situations were measured with a slider ranging from 1,000 K to 14,000 K. The slider's initial position matched the current color temperature setting of the room lighting (1,600 K or 13,000 K). To assist participants with their selection, a color gradient was provided in the form of a scale ranging from reddish to bluish, which corresponded to the blackbody curve. Thirteen situations were used to cover different scenarios, such as working alone, working in a group, relaxing alone, relaxing in a group, negotiating a personal situation with someone, negotiating a business deal, and so on (see Table 14).

7.4 Setting and Procedure

The apparatus used was a 14-inch Dell LCD notebook with screen size 31 cm x 17.5 cm and 1280 x 800 pixel resolution, screen brightness 250 cd/m^2, sRGB color space and refresh rate of 60 Hz, which was placed on a table in a 12.5 m^2 office room without any daylight to avoid confounding variables. The light sources were two LED spotlights (Protech Multi PAR, 7x4 W Edison RGBW LEDs, 45° radiation angle) using additive color mixing technology. The two light sources were mounted above the participant and uniformly illuminated the field of vision. Study CH1 made use of more subtle lighting conditions, but in Study CH2, the lighting was immersive and noticeable, though the illumination level was the same as in Study CH1 (450 lx). In this research, the two levels of the independent variable used in different blocks of the experiment were a very warm color temperature of approximately 1,600 K ($x = 0.496$, $y = 0.315$, CRI [R_a] = 63) and a very cold color temperature of approximately 13,000 K ($x = 0.294$, $y = 0.237$, CRI [R_a] = 27).

In the experimentation room, participants were requested to sit on a chair to work comfortably with the laptop. The description of a conflict-related situation and the subsequent questions were displayed on the laptop screen using an online survey application. Participants were instructed to familiarize themselves with one of the two pre-selected conflict situations and to imagine that they were experiencing the situation. First, the participants were instructed to complete a SAM consisting of three sets of non-verbal pictorial assessment questions to rate the affective dimensions of valence, arousal, and dominance associated with participants' reactions to the combination of conflict case and room lighting. Thus, the SAM measured participants' current feelings. This was followed by a slider scale ranging from 1,000 K to 14,000 K color temperature that indicated the participants' general lighting preference in the 13 situations. To visualize the color temperatures, the scale was made into a transitional color graph ranging from reddish to bluish color.

After this, the conflict case was reintroduced, and the participants were asked to complete the 30 questions from the TKI, along with additional questions related to the changes they perceived in their motivation levels, creativity, comfort, happiness, and anxiousness.

The conflict scenarios used were the same as in Study CH1. (1) negotiating a disagreement with their landlord over a leaky faucet or (2) negotiating with an uncooperative fellow student as the deadline of a joint presentation approaches. After both scenarios have been completed, the participants were requested to report if they perceived any changes in the lighting conditions between the two blocks and if this change affected their emotion and creativity levels using a bipolar 5-point semantic scale. Finally, another set of slider scales was employed, similar to the one administered at the beginning of the experiment, to measure if the change in color temperature affected participants' emotional states (Houser & Tiller, 2003; Wu & Wang, 2015).

The experiment took approximately two hours in total, with two 50-minute blocks separated by a 10-minute break. During the break, the participants were asked to sit outside the experimentation room on a couch in the lobby and were then guided back into the room by an experimenter for the second session. The color temperature of the lighting in the test room was changed from warm to cold or vice versa by the experimenter during the break between the two sessions without the participants' knowledge. The illuminance level was constant and remained at approximately 450 lux. The procedure of the second session was similar to the first one.

7.5 Results

7.5.1 SAM and emotional states

A paired t-test indicated a slight effect of lighting condition on pleasure level, $t(67) = 2.234$, $p = .029$, $d_z = 0.27$. The other SAM items such as dominance, $t(67) = -1.292$, $p = .201$, $d_z = -0.15$, and arousal, $t(67) = -1.831$, $p = .072$, $d_z = -0.22$, revealed no significant variations (see Tables A10, A11).

A structural equation model was used to investigate the effect of lighting on SAM levels and used all three SAM variables as dependent variables. In addition, the influence of the “Lightning Condition” and “Block” was included directly in the model. Results showed no significant results at $p < .05$ but a weak significant correlation at $p < .10$ between the lighting condition and pleasure scale, $b = -0.154$, $p = .065$. In other words, when the lighting changed from reddish to bluish, the value on the SAM pleasure scale decreased by -0.154; this indicates that the participants considered themselves happier when the lighting changed from reddish to bluish. The correlations between the individual SAM scales (see Table A12) were significant in all three cases ($p < .001$). The correlation between SAM dominance and SAM pleasure was very weak, yet significant, $r = .079$, $p < .001$, $N = 68$. Whereas the other two combinations had a slightly positive (the higher the dominance, the higher the arousal, $r = .369$, $p < .001$, $N = 68$, and a negative (the higher the arousal, the lower the pleasure, $r = .349$, $p = .000$, $N = 68$) correlation.

Since it was difficult to make conformational statements with the available data, this analysis can best be described as exploratory. The five queries on the current emotions were evaluated with a paired t-test (see Tables A13, A14). There were no significant differences between the reddish and bluish lighting ($p < .05$) for motivation ($t(67) = -1.734$, $p = .087$), creativity ($t(67) = -0.686$, $p = .495$), comfort ($t(67) = -1.107$, $p = .272$), and anxiousness ($t(67) = -0.234$, $p = .816$). However, there was a weak effect at an extended significance level ($p < 0.10$) for happiness ($t(67) = -1.855$, $p = .068$, $d_z = -0.23$). This is in line with the findings of the SAM test for pleasure ($t(67) = 2.234$, $p = .029$, $d_z = 0.27$).

7.5.2 Conflict handling style (TKI)

A general linear model was employed to investigate the influence of lighting conditions on the five conflict styles (competing, collaboration, compromising, avoiding, and accommodating), and their individual characteristics across four cohorts. The lighting conditions (reddish or bluish lighting), conflict case (student or landlord conflict,) and block position (before or after the intermission) were used as between-subject factors to identify the interaction effects between the different conflict cases and blocks. The results of this analysis revealed an interaction effect between the different conflict cases and blocks. Additionally, paired *t*-tests were conducted to examine the effects of lighting condition on each conflict style within the subjects.

Competing

As shown in Tables 9 an 10 the main effect of the block was significant, $F(1, 128) = 5.055$, $p = .026$, $\eta_p^2 = .038$, independent of the conflict case and lighting condition. The value of competing for block 2 ($M = 6.544$, $SD = 3.25$) was significantly higher than for block 1 ($M = 5.324$, $SD = 3.36$). The null hypothesis H1a must be retained.

Table 9

Tests of between-subjects factors for competing CH2

Source	*SS*	*df*	*MS*	*F*	*p*
LightingCondition	1.654	1	1.654	0.165	.685
Case	11.184	1	11.184	1.116	.293
LightingCondition × Case	23.890	1	23.890	2.384	.125
Block	50.654	1	50.654	5.055	.026*
LightingCondition × Block	17.654	1	17.654	1.762	.187
Case × Block	126.184	1	126.184	12.593	.001**
LightingCondition × Case × Block	0.596	1	0.596	0.059	.808

Note. $N = 68$; * $p < .05$, ** $p < .01$.

Table 10

Block main effect for competing CH2

Block	*M*	*SE*	95% *CI*	
			LL	*UL*
1	5.324	0.384	4.564	6.083
2	6.544	0.384	5.785	7.304

Note. $N = 68$.

A two-way analysis of variance revealed a significant difference between the block and conflict case, $F(1, 128) = 12.593$, $p = .001$, $\eta_p^2 = .090$. Specifically, the competing style was higher in block 1 for the student case ($M = 6.000$, $SD = 3.44$) and lower for the landlord case ($M = 4.647$, $SD = 3.19$), whereas in block 2 it was the other way round, i.e., competing value was higher in the landlord conflict case ($M = 7.794$, $SD = 3.21$) and lower in the student conflict case ($M = 5.294$, $SD = 2.81$, see Table A15). Furthermore, neither a significant influence of the lighting condition on competing style was found between-subjects, $F(1,128) = 0.165$, $p = .685$, $\eta_p^2 = .001$, nor within-subjects using a paired *t*-test, $t(67) = 0.388$, $p = .699$.

Collaborating

As shown in Tables 11 and A17, there was a significant effect of the conflict case, $F(1,128) = 4.271$, $p = .041$, $\eta_p^2 = .032$, and the interaction of conflict case and block, $F(1,128) = 11.864$, $p = .085$, on the style. Participants tended to be more collaborative in the student conflict case ($M = 6.118$, $SD = 1.90$) compared to the landlord conflict case ($M = 5.456$, $SD = 2.06$). The null hypothesis H1b must be retained.

Table 11

Tests of between-subjects factors for collaboration CH2

Source	*SS*	*df*	*MS*	*F*	*p*
LightingCondition	1.654	1	1.654	0.475	.492
Case	14.890	1	14.890	4.271	.041*
LightingCondition × Case	1.654	1	1.654	0.475	.492
Block	13.596	1	13.596	3.900	.050
LightingCondition × Block	12.360	1	12.360	3.545	.062
Case × Block	41.360	1	41.360	11.864	.001**
LightingCondition × Case × Block	7.066	1	7.066	2.027	.157

Note. $N = 68$;* $p < .05$, ** $p < .01$.

The mean value for collaboration in block 1 was higher for the student case ($M = 6.353$, $SD = 1.89$) compared to the landlord conflict case ($M = 4.588$, $SD = 1.78$). In block 2, however, the collaborating value for the landlord case ($M = 6.324$, $SD = 1.97$) was higher than that of the student conflict case ($M = 5.882$, $SD = 1.90$). A between-subject, $F(1, 128) = 0.475$, $p = .492$, $\eta_p^2 = .004$, and a within-subject paired *t*-test, $t(67) = 0.707$, $p = .482$, showed no significant influence of lighting condition on the collaborating style (see Table A16).

Compromising

A between-subject analysis, $F(1, 128) = 0.741$, $p = .391$, $\eta_p^2 = .006$, and a paired t-test, $t(67) = -0.793$, $p = .430$, revealed no significant influence of the lighting condition on the compromising style (see Table A18). The null hypothesis H1c must be retained.

Avoiding

As displayed in Tables 12, A19 and A20, there was a marginally significant effect of block position to avoiding style, $F(1, 128) = 3.997$, $p = .048$, with mean values increasing from block 1 ($M = 7.074$, $SD = 2.11$) to block 2 ($M = 6.397$, $SD = 1.78$). The null hypothesis H1d must be retained.

Table 12

Tests of between-subjects factors for avoiding CH2

Source	*SS*	*df*	*MS*	*F*	*p*
LightingCondition	0.029	1	0.029	0.008	.931
Case	0.265	1	0.265	0.068	.795
LightingCondition × Case	1.882	1	1.882	0.484	.488
Block	15.559	1	15.559	3.997	.048*
LightingCondition × Block	2.941	1	2.941	0.756	.386
Case × Block	7.529	1	7.529	1.934	.167
LightingCondition × Case × Block	0.029	1	0.029	0.008	.931

Note. * $p < .05$, ** $p < .01$.

An ANOVA revealed no significant three-way interaction effect of the lighting condition, conflict case, and block on the conflict avoidance style, $F(1, 128) = 0.008$, $p = .931$, $\eta_p^2 < .001$. A paired t-test showed no significant effect of the lighting condition on the avoiding conflict style, $t(67)= -0.087$, $p > .931$. In addition, unlike Study CH1, there was no significant difference between the student case in warm/reddish values and the landlord case in cold/bluish conditions, $F(1, 128) = 0.484$, $p = .488$, $\eta_p^2 = .004$.

Accommodating

There was a significant main effect of block, $F(1, 128) = 3.988$, $p = .048$, $\eta_p^2 = .030$, as well as a significant interaction between block and lighting condition, $F(1, 128) = 9.561$, $p = .002$, $\eta_p^2 = .070$, and case and block, $F(1, 128) = 31.411$, $p < .001$, $\eta_p^2 = .197$, in the accommodating style (see Tables 13, A21, A22, A23). The accommodating style decreased significantly in block 2 ($M = 3.971$, $SD = 2.87$) compared to block 1 ($M = 4.882$, $SD = 3.11$).

Table 13

Tests of between-subjects factors for accommodating CH2

Source	*SS*	*df*	*MS*	*F*	*p*
LightingCondition	0.118	1	0.118	0.017	.898
Case	2.382	1	2.382	0.336	.563
LightingCondition × Case	0.471	1	0.471	0.066	.797
Block	28.265	1	28.265	3.988	.048*
LightingCondition × Block	67.765	1	67.765	9.561	.002**
Case × Block	222.618	1	222.618	31.411	.000**
LightingCondition × Case × Block	0.471	1	0.471	0.066	.797

Note. $N = 68$; $*p < .05$, $**p < .01$.

In block 1, participants exhibited lower levels of accommodation for the reddish lighting condition ($M = 4.147$, $SD = 3.14$) than for bluish lighting condition ($M = 5.618$, $SD = 2.94$). In block 2, however, the average value of accommodation in reddish lighting ($M = 4.647$, $SD = 3.16$) was higher than that in bluish lighting ($M = 3.294$, $SD = 2.41$).

There was a significant interaction effect between case and block. In block 1, the mean value for the student conflict case ($M = 3.735$, $SD = 2.83$) was significantly lower than for the landlord conflict case ($M = 6.029$, $SD = 2.99$). However, in block 2, the mean value of accommodation for the student case ($M = 5.382$, $SD = 2.72$) was higher than for the landlord case ($M = 2.559$, $SD = 2.29$). Additionally, in block 2 the mean of accommodation value for the student case (M = 5.382, SD = 2.72) was significantly higher than in block 1. A between-subject, $F(1, 128) = 0.017$, $p > .898$, $\eta_p^2 < .000$, and a within-subject paired t-test, $t(67) = -0.129$, $p > .898$, showed no influence of lighting condition on the accommodating conflict handling style. The null hypothesis H1e must be retained.

With regard to the independent variable of the lighting situation to be investigated, no direct and significant influence on the respective manifestations of conflict handling styles can be confirmed.

7.5.3 Lighting preferences

ANOVA

The ANOVA revealed the overall significance of lighting preferences for the 13 situations based on slider values, $F(12, 1755) = 8.806$, $p < .001$. However, the adjusted R-squared value of .050 indicates that the variance explained by the different situations was relatively low. Nonetheless, significant contrasts were found among certain situations, which are presented in Table A24.

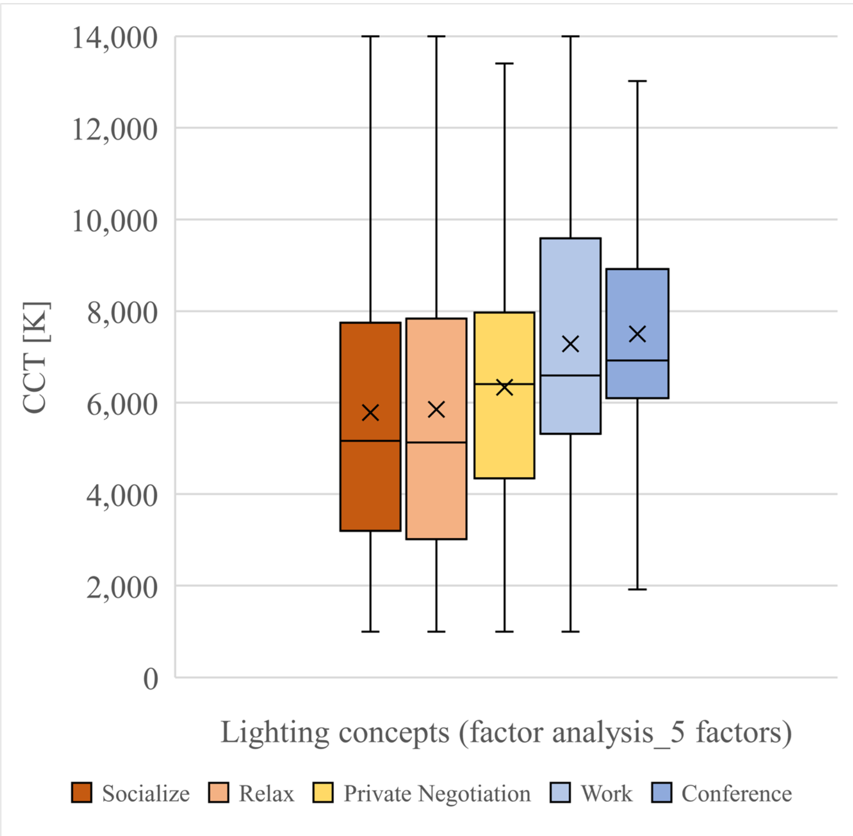
Cluster and factor analysis

In addition to the ANOVA, a k-means cluster analysis was performed to detect homogeneous groups of situations based on chosen lighting preferences. These were calculated in steps of two, three, and four clusters. The 2-cluster solution yielded quite different numbers of cases, as did the 3-cluster and 4-cluster solutions. Finally, a factor analysis was calculated to better reveal the structure of the slider-based lighting preference choices (see Table A25).

It showed a total of five factors or correlated situations based on lighting preferences. In line with predictions regarding congruent conceptual lighting, Factor 1 consisted mainly of socializing situations with a preference for warmer lighting, as compared to Factor 2 which consisted of work-related situations with a preference for cooler lighting. Further results are depicted in Figure 9 and Table 14. The identified factors supported that lower color temperatures were preferred for socializing (M = 5788.03, SD = 3277.98) and relaxing situations (M = 5852.03, SD = 3644.96) rather than to performance-related work (M = 7283.94, SD = 3091.25) and conference situations (M = 7499.32, SD = 2694.66).

Figure 9

Lighting preferences: lower CCT for private and higher CCT preferred for work-related scenarios



Note. N =68.

Table 14

Factor analysis lighting preferences CH2

		Factors				
		1	2	3	4	5
Item	Situation	Socialize	Work	Conference	Relax	Private Negotiation
1	Personal desktop tasks		0.723			
2	For everyday office desktop tasks alone		0.948			
3	Everyday office desktop tasks with colleagues/fellow students		0.686			
4	Negotiating a personal situation with someone					0.579
5	Negotiating a business deal					
6	Team meeting with colleagues / fellow students					
7	Networking at a conference meeting			0.869		
8	Formal business networking in an office / boardroom setting			0.786		
9	Informal business networking in a lounge setting	0.601				
10	Hanging out with friends at a bar	0.571				
11	Meeting with friends in one´s living room	0.567				
12	Taking a relaxing break during work				0.907	
13	Relaxing at home				0.876	

8. Study 3 (CH3): Combined experiment analysis

8.1 Participants

The data from the two studies were merged further for a combined analysis. Accordingly, the sample size was $N = 136$ (88 males, 48 females, $M = 25.16$ years, $SD = 3.14$ years), with participants' details reported in Sections 6.2 and 7.2.

8.2 Measures

Measurements of recent emotions and TKI were taken from the previous studies (see Section 6.3 and 7.3).

8.3 Procedure and material

Due to the similar design of Study CH1 and Study CH2, the data allows for a combined analysis of subtle vs. noticeable lighting on conflict handling styles. Thus, the illumination of 2,500 K versus 3,800 K (ΔCCT = 1,300 K) from study CH1 was associated with 1,600 K versus 13,000 K (ΔCCT = 11,400 K) from study CH2. In both experiments the illuminance was constant at 450 lx. The basic structure of comparing a warm or reddish illumination with a cold white or bluish illumination was consistently implemented in both studies. The warm white and reddish illumination were combined to a new variable, "Low CCT" and the cold white and bluish illumination to "High CCT".

8.4 Results

Emotional states

The five queries on current emotional states were evaluated with a paired *t*-test. There were no significant differences ($\alpha = .05$) in emotions between high CCT (cold and bluish lighting) and low CCT (warm and reddish lighting) for motivation, $t(135) = -1.322$, $p = .187$, creativity, $t(135) = -0.194$, $p = .846$, comfort, $t(135) = -0.051$, $p = .959$, happiness, $t(135) = -0.051$, $p = .550$, and anxiousness, $t(135) = 0.115$, $p = .909$, see Table A26 and A27.

Conflict handling style (TKI)

The analysis of variance in the combined data sets of 136 subjects with each subject measured in a low and high CCT environment, indicated no significant influence of color temperature for the competing ($F(1,270) = 1.043$, $p > .308$, $\eta^2_p = 0.004$), collaborating ($F(1,270) = 0.373$, $p > .542$, $\eta^2_p = 0.01$), compromising ($F(1,270) = 0.057$, p > .812, $\eta^2_p = 0.000$), avoiding ($F(1,270) = 0.706$, $p > .402$, $\eta^2_p = 0.003$), and accommodating style ($F(1,270) = 0.687$, $p = .408$, $\eta^2_p = 0.003$) as shown in Tables A28 and A29.

9. Discussion

9.1 Effects on conflict handling style

The results, based on two empirical studies and the combined analysis, support that conflict handling behavior is quite stable and not easily influenced by lighting conditions. Each of the five measured characteristics of the TKI conflict styles remain unaffected by the prevailing lighting situation. However, certain combinations of lighting condition, block order, and conflict case affected avoiding and accommodating styles in Study CH1.

In Study CH1, the avoiding style was significantly affected by warm and cold color temperatures and the presented conflict case ($p = .002$, $\eta^2_p = 0.075$). A conceptual lighting condition incongruent with the implicit expectation for the situation (work vs. private) based on repeated occurrences in daily life led to an increase in avoidance behavior. In the second study, extreme color temperatures that did not simulate the ones encountered in daily life situations did not produce a significant effect. In contrast, accommodating behavior was influenced by block position in connection with the lighting condition in both experiments. This effect was stronger ($p < .001$, $\eta^2_p = 0.197$) in the second experiment than in the first one ($p =$

.027, $\eta^2_p = 0.037$). This result can be interpreted as an indication of limited resources for dealing with conflicts, which depletes in the second block, especially under extreme environmental conditions (extreme reddish and bluish room lighting). However, only the interaction effects were significant. There was no significant main effect of lighting condition on conflict handling styles, and this was further supported by the combined analysis.

In current research studies, there are various descriptions of the influences of lighting on psychological variables, such as self-perception, emotion, and performance. However, the previous study results demonstrate that these effects cannot be directly applied to complex constructs such as conflict management style, underscoring the need for further research. Moreover, conflict behavior is also determined by intrinsic factors, such as personality traits and cultural conditioning (Ayub et al., 2017; Gbadamosi et al., 2014; Thomas et al., 2008; Zhenzhong, 2006), and to a lesser extent by external factors, such as the situation and the environment (Baron, 1990; Steidle et al., 2013). As reported above, decreasing accommodating behavior was observed when the task of conflict resolution was assigned for the second time, regardless of the type of conflict or lighting condition, thus indicating a reduction in assertiveness over time. The results also support that there is limited influence of particular environmental factors on complex behavioral constructs.

9.2 Conceptual lighting settings

The participants seemed to withdraw and act more passively under incongruent conceptual lighting (student conflict in warm lighting instead of cold, and landlord conflict in cold lighting instead of warm) compared to congruent conceptual lighting conditions. This observation was significant in Study CH1. Oftentimes, work environments have fluorescent tube-lights with neutral or cold color temperatures (above 3,500 K), while private spaces such as bedrooms/living-rooms utilize warm lights with lower color temperatures (below 3,500 K).

Repeated exposures to such pairings in the environment leads to a mental representation (concept) of lighting-space congruency.

The extreme reddish (1,600 K) and bluish electric illumination (13,000 K) of Study CH2 is not usual in everyday situations and therefore has no parallels to existing concepts in daily life. The lighting situations of the first experiment are thus closer to the real-life settings of the participants and, in the case of an incongruent appearance, led to an avoiding conflict handling style. The survey of lighting preferences in different real-life situations and the factor analysis reported above confirm that everyday situations have associated lighting preferences that lead to the concept of conceptual and counter-conceptual lighting over time; this is in line with existing scientific results about prevailing environmental conditions (Biner et al., 1989; Butler & Biner, 1987; Gomes & Preto, 2015). Although the CCT values of lighting preferences for socializing and relaxing is rather high, it is significantly lower than those chosen for work-related scenarios.

Moreover, it is difficult for untrained individuals to classify their lighting preference in CCT values, despite the additional hints provided. The participants were provided with the CCT value corresponding to the current lighting setting of the room and a visual representation in form of a color gradient over the slider. The results support findings based on biological expectations that higher light temperature is associated with improved cognitive performance and is assigned to work-related situations; this is in line with various psychological and neurological studies (Cajochen et al., 2011; Lehrl et al., 2007; J. Lin et al., 2020; Lockley et al., 2006; Motamedzadeh et al., 2017; Sahin & Figueiro, 2013; Vandewalle et al., 2013; Viola et al., 2008).

9.3 Emotional states

The observed weak tendency ($p < .10$) for higher happiness in bluish lighting conditions compared to reddish conditions can be explained by conceptual situational-lighting and space-lighting congruency. Bluish light has been associated with higher cognitive performance; thus, having blue light in a test situation may have elevated the emotions of student participants. Regarding space-lighting congruency, university buildings normally use inherent neutral to cold white illumination. Thus, the illumination in the higher CCT range is more aligned to the experiences and expectations of student participants compared to warm-white (2,500 K) and reddish (1,600 K) illumination.

In contrast, Wu and Wang (2015) report an increase in pleasure levels at warm color temperatures in a private, non-performance-oriented setting (restaurant).These results can be explained by expectation-oriented and concept-congruent lighting for relaxed non-work-related scenarios. Thus, it is not the color temperature of the lighting *per se* but how well it matches the conceptual models and expectations of lighting for a given task or situational needs and the location or setting.

9.4 Limitations

Conflict style was recorded by a standardized self-assessment inventory for imagined conflict scenarios and not by observing actual behavior. Although this is an established empirical procedure in line with other studies on conflict handling and lighting (e.g., Baron et al., 1992; Kombeiz et al., 2017), it may provide a limited indication of the actual expression of the measured behavior. In addition to the noted cultural influences on conflict management, there are also intercultural differences in lighting preferences. According to Park et al. (2010), for example, there are differences between North Americans and South Koreans in their preference for the brightness of warm lighting for informal activities. As Kombeiz et al. (2017) notes, cultural differences can mask the effects of lighting influences. More cross-cultural studies would be necessary for global validity.

Conflict handling styles can be considered a psychological outcome that generally occurs with small effect sizes. The analysis of sample sizes of previous relevant studies and the power analysis of the present study reveals that the detection of small effect sizes is challenging and limits the strength of studies. Therefore, future studies should aim to increase statistical power to detect psychological effects with small effect sizes; this results in higher requirements for the sample size than was usual in former laboratory studies.

The light exposure durations were comparable to other lighting studies (Borragán et al., 2017; Kombeiz et al., 2017; Kombeiz & Steidle, 2018). A longer exposure time could increase the non-image function effect of lighting participants. However, there is a practical limitation on the duration of laboratory studies in relation to ethical appropriateness and reasonableness towards the participants. Wilms and Oberfeld (2018) report in their study with LED panels that research on emotional effects of colored lighting is complex, and one needs to consider hue, saturation, and brightness. Physiological measurements such as heart rate, skin resistance, and so on have not been recorded, and thus lighting conditions cannot be examined for their somatic effects.

9.5 Future research

To transfer the influence of isolated environmental factors like concrete lighting conditions to complex constructs like conflict behavior, it is necessary to identify the different moderating variables and to assess their impact. De Kort (2019) and Veitch et al. (2019) published recommendations for standardized basic conditions of prospective lighting experiments. These should be considered accordingly and be followed in further experiments.

A causal relationship by which a high or low color temperature makes individuals more assertive, more cooperative, or happier cannot be assumed. Moreover, the results indicate that higher or lower illuminances, color temperatures, and so forth should be studied in association with the expectations for respective situations, tasks, and locations, offering an interesting venue for further interdisciplinary research.

10. Conclusion

Conflict handling seems to be a stable construct that cannot be influenced by the tested lighting conditions as a determining environmental factor. Individuals have different preferences for lighting in recreational and performance-oriented situations. A lighting condition can therefore be conceptually congruent and thus adequate to an individual's expectations. According to our results, higher and performance enhancing CCT values in a work environment and lower CCT values in a recreational environment are conceptually congruent. Counter-conceptual lighting may lead to an avoiding conflict handling style, but more research is required to explore this complex phenomenon.

PART III EXPERIMENTAL STUDIES: EXPLORING EFFECTS OF LIGHTING IN VIRTUAL SPACES

The following chapters address the state of research in lighting and especially in virtual spaces. A literature review provide insights into the contemporary state of lighting research in physical and virtual spaces and highlights the challenges of lighting research in virtual space. Two studies, abbreviated VL1 and VL2 for virtual lighting Study 1 and Study 2, serve as the basis for investigating the effects of virtual lighting, particularly CCT and virtual daylight. In Chapter 14, these two studies are compared and analyzed (Study VL3) for the development of an approach and model draft in Chapter 15. Each chapter includes its own background, methodology, discussion, and conclusion. These chapters have been prepared for publication in peer-reviewed journals, are under review, or have already been published.

11. Literature Analysis: Understanding psychological mechanisms to improve virtual spaces and Metaverse events

11.1 Introduction

In recent years people have shifted several activities online (Damar, 2021), like meetings and events into virtual spaces. For instance, due to the COVID-19 pandemic, many scientific conferences have been shifted from physical to online events (Falk & Hagsten, 2020). Online events can be distinguished between streaming formats, video conferencing, and events that take place in a three-dimensional virtual space that can be accessed via an avatar. These latter spaces can be part of a Metaverse, which is an immersive virtual world using the metaphor of the real world but without its physical limitations (A. Davis et al., 2009).

These three-dimensional spaces are especially exciting for future research because they can be individually designed. Beyond the technological aspects, these developments are also interesting from a psychological point of view. Users perceive them as an environment comparable to an immersive computer game. Hence, these environments can influence users' emotions and behaviors (Slater, 2009).

Research on perception can make an important contribution to evaluating and improving virtual environments and Metaverse events. Psychology is therefore an increasingly relevant factor in designing human-centered meeting environments and should be given greater consideration This can be pursued as a systematic approach to linking psychology and event management, known as event psychology (Ronft, 2021a; Wrobel & Winnen, 2021). Regarding the complexity of psychological mechanisms, the following approaches focus on psychology of perception, environmental psychology and visual communication. For example, lighting is an essential component of the perception of spaces and is well studied regarding its psychological and biological effects (e.g. Westland et al., 2017; Tomassoni et al., 2015).

This chapter identifies and discusses the status quo and challenges of adapting scientific methods from the physical environment to virtual environments. Emphasis is placed on the transferability of items and scales for space perception. Additionally, the technical limitations and challenges of research in virtual environments are highlighted. Lastly, the prerequisites for improving virtual spaces and events are noted.

11.2 Theoretical Background

11.2.1 Virtual spaces and Metaverse events

"Virtual worlds" are defined by Dionisio et al. (2013) as persistent, computer-generated environments for multiple users, in remote physical locations, to interact in real time for working or gaming purposes. As the elaboration on the forecasted evolution of virtual environments and Metaverses as well as AR, and VR applications in Section 2.5.6 indicate, this will be a relevant topic for millions of new users in the coming years. The number of trade shows, product launches, press conferences, corporate meetings, and other events such as concerts that are already purely virtual or hybrid are expected to increase. Consequently, virtual environments and associated technologies are actively being discussed in event management (Drengner & Wiebel, 2020) and have been identified as a topic of future research (Drengner, 2022; Wreford et al., 2019).

11.2.2 Environment as an influencing factor of psychological mechanisms

Psychological effects on social interaction in virtual spaces

The human psyche is a complex entity and is influenced by many extrinsic and intrinsic factors. In addition to intrinsic prerequisites such as memories, experiences, and prior knowledge, extrinsic stimuli from the environment also have an effect on people. These stimuli are processed cognitively and emotionally, creating a perceived subjective reality. Humans are used to moving and interacting in a physical environment. In virtual environments, however, some of these behaviors can only be transferred to a limited extent. Depending on the technical platform, for example, freedom of movement and interaction with other people are limited. Instead of social communication, which largely takes place non-verbally via facial expressions and gestures (Solowjew, 2021), users have to resort to pre-defined reaction buttons, texts, and video chats.

Technologies such as facial expression recognition (FER), which relies on optical cameras, or facial electromyogram (fEMG), which relies on electrodes to detect electrical activity through facial muscle movements, enable the mirroring of human facial expressions onto an avatar (H.-S. Cha & Im, 2022). Beyond these approaches, platforms such as doob meta xr use a "speech to mimic" feature (doob group AG, 2022) that provides an imitation of corresponding facial expressions through an artificial intelligence (AI) based voice analysis. However, in the virtual imitation of mimic and gesture multiple psychological mechanisms become apparent, such as the ‘Uncanny Valley effect’ (Mori et al., 2012). This effect describes implicit expectations of verbal and nonverbal responses from a human-looking robot or avatar that cannot be met by a non-human conversation partner due to nowadays technical capabilities. Unexpected responses from robots or avatars can trigger a feeling of uncanniness and rejection.

As illustrated by these complex mechanisms, the social-psychological consideration of virtual space is a comprehensive topic. Since visual communication is a key element of virtual social interaction, visual perception in virtual spaces is highly relevant.

Psychological effects of visual perception and lighting

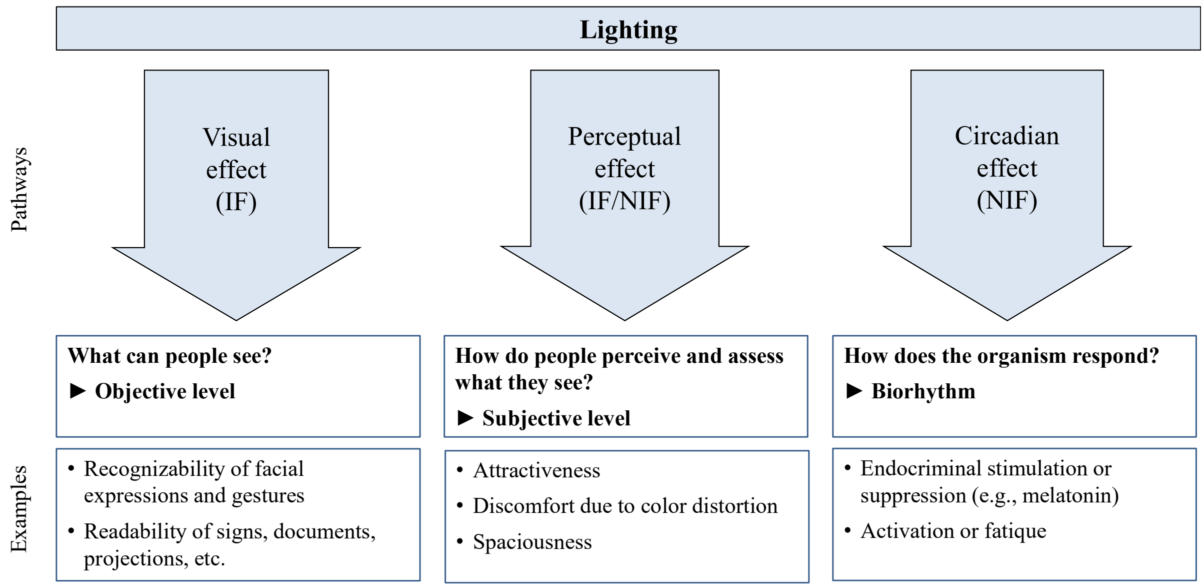
Humans perceive their visual environment via light-sensitive rods and cones in the retina that synthesize an image. In the physical environment, visual information is absorbed via light reflections from daylight or electric lighting on objects. In virtual spaces, a display emits the necessary light stimuli. Regardless of whether visual stimuli originate from reflections or displays, in addition to the perceptual processes, biological and psychological implications can be assumed.

The biological and psychological effects of lighting can be divided into visual effects, perception effects and circadian effects (see Fig. 10). On an objective level, the visual path influences which information can be perceived visually. In contrast, the perceptual path describes the subjective perception of perceived information. Finally, the circadian path describes effects on the human organism. By stimulating or suppressing the production of hormones such as melatonin, humans are activated or fatigued. Hence, parameters of lighting, such as color temperature, brightness, and so on, impact people's daily lives and can determine their emotions (Ronft, 2021b).

For example, blue-enriched lighting has an impact on alertness and cognitive performance due to melatonin suppression (Chellappa, Steiner, et al., 2011). Recent studies have also indicated that lighting has an impact on perceived comfort and temperature (Bluyssen et al., 2011; Chraibi et al., 2016; Huebner et al., 2016).

Figure 10

Image-forming (IF) and non-image forming (NIF) pathways of lighting effects



Note. Adapted from Ronft, 2021b, p. 213

Effects on cognitive performance and affective states have already been documented by various studies and are the subject of lively debate (e.g., Baron et al., 1992; Hawes et al., 2012; Hygge & Knez, 2001; Knez, 2001; Knez & Enmarker, 1998; Kretschmer et al., 2012). Recent studies have also provided concrete indications of which lighting conditions can be stimulating or inhibiting for interactions and cooperative behavior (Kombeiz et al., 2017; Ronft & Ghose, 2018, 2019; Steidle et al., 2013).

Visual perception is important for spatial orientation processes and thus navigation (Hidayetoglu et al., 2012; Suzer & Olgunturk, 2018). Virtual spaces, unlike physical spaces, do not require physical-realistic light sources to enable visual orientation. However, in the context of game design, the effects of virtual lighting on orientation are also investigated (Knez & Niedenthal, 2008; Marples et al., 2020). Further psychological mechanisms are increasingly being explored.

11.3 Current research discourses

11.3.1 Scope of literature review

A literature review was used to compare existing instruments for measuring the psychological effects of lighting, to discuss their transferability for virtual environments, and their implications for the design of virtual spaces. The literature reviewed ranges from journal articles on light research from the 1970s to present-day research on virtual spaces and information technologies. In a next step, market statistics and technical specifications of visual devices were reviewed to reflect the relevance to the present research field and provide preparatory information for conducting further studies in this thesis (see Chapters 12 and 13). The literature analysis presented in this chapter, focusing on lighting research instruments and scales, does not claim to be a meta-analysis according to guided protocol methods such as PRISMA (Page et al., 2021; Shamseer et al., 2015) or STARLITE (Booth, 2006).

11.3.2 Instruments and scales to measure psychological effects of lighting

There are various instruments and scales for measuring the psychological effects of lighting. The literature review indicated that semantic differential rating scales are common for subjective assessment of perceived environments. However, questionnaires differ in the following parameters: level of scaling, polarity of semantic differential scale, number of items, source of adaptions, and environments of investigation.

Many of the instruments used today are based on lighting research by Flynn (Flynn et al., 1973; Flynn et al., 1979; Flynn & Spencer, 1977), who developed a bipolar 7-point semantic differential rating scale. This itemset and rating scale, which was analyzed via factor analysis (Flynn & Spencer, 1977), is the basis for contemporary questionnaires (see Table 15).

Table 15

Overview of questionnaires to assess the psychological effects of lighting in virtual and physical environments

Questionnaire	Level of scaling	Polarity of semantic differential scale	Number of items	Adapted from	Environment of investigation
Abd-Alhamid et al., 2019	5-point	bipolar	12	Cauwerts, 2013; Liang et al., 2019; Kuang et al., 2005; Odabaşioğlu & Olguntürk, 2015	virtual & physical
Canazei et al., 2016	4-point 6-point 4-point	unipolar bipolar unipolar	38 6 1	Vogels, 2008 Cervinka et al., 2009	physical
Chamilothori et al., 2019	5-point	unipolar	13	Flynn et al., 1973; Vogels, 2008; Rockcastle et al., 2017	virtual
Y. Chen et al., 2019	7-point	bipolar	12	Flynn et al., 1979	physical & virtual
Flynn & Spencer, 1977	7-point	bipolar	19	Flynn et al., 1973	physical
Flynn et al., 1973	7-point	bipolar	34	-	physical
Flynn et al., 1979	7-point	bipolar	30	Flynn & Spencer, 1977	physical
Hendrick et al., 1977	7-point	bipolar	27	Flynn et al., 1973	physical
Knez & Niedenthal, 2008	5-point	unipolar	10	-	virtual
Loe et al., 1994	VAS	bipolar	10	Flynn et al., 1973	physical
Mahdavi & Eissa, 2002	7-point	unipolar	10	Flynn et al., 1973	physical
Newsham et al., 2004	VAS	bipolar	15	Hendrick et al., 1977; Veitch & Newsham, 2000; Loe et al., 1994; Mahdavi & Eissa, 2002	virtual
Newsham et al., 2005	VAS	bipolar	15	Newsham et al., 2004	virtual
Newsham et al., 2010	VAS	bipolar	4	Hendrick et al., 1977	virtual
Odabaşioğlu & Olguntürk, 2015	5-point	bipolar	36	Flynn et al., 1973; Flynn et al., 1979; Flynn & Spencer, 1977; Yildirim et al., 2007	physical
Rockcastle et al., 2017	7-point	bipolar	7	Flynn et al., 1979	virtual
Vogels, 2008	5-point 7-point	bipolar bipolar	9	Flynn & Spencer, 1977	physical
Yildirim et al., 2007	5-point	bipolar	8	-	physical
Zimmons, 2004	7-point	bipolar	15	Flynn et al., 1979	virtual

Note. VAS = Visual Analogue Scale, which is scored with values from 0 – 100.

Knowing Flynn´s results, other instruments were developed and validated with additional procedures. For instance, Vogels' atmosphere questionnaire (2008) uses a principal component analysis (PCA) to gain insight into the underlying dimensions of the various item terms. To promote international applicability of the atmosphere questionnaire, a lexicon was compiled to describe relevant terms. In Vogels' publication, the discriminatory power of the items was also tested by conducting the questionnaire in 11 different physical spaces. This intensive testing of a measurement instrument is rather an exception. Lighting studies usually rely on the instruments and scales used in comparable studies or well-documented and therefore replicable approaches such as those of Flynn and Spencer (1977) or Vogels (2008).

Reliable methods from psychological research are also used to measure emotions in lighting research. Established tests such as the SAM are used to determine the effect of light on emotions (Ronft & Ghose, 2018, 2019; Wilms & Oberfeld, 2014; Wu & Wang, 2015). The nonverbal SAM inventory uses pictograms to classify a person's state of mind. Such tests are credited as being able to be used cross-culturally and regardless of the subject's language level (Morris, 1995). To gain further insight into emotional states not captured by the SAM test, self-reports on semantic scales are obtained. For example 5-point bipolar semantic differential scales with values ranging from -2 (i.e., indicating low motivation) to +2 (i.e., indicating high motivation; 0 = neutral) allow scoring for affect labels like motivation, creativity, comfort, happiness and anxiousness (Houser & Tiller, 2003; Wu & Wang, 2015).

11.3.3 Usage behavior and technical specifications of devices

Research that investigates effects in virtual space needs to consider the technical specifications and usage of devices. For this purpose, a review of technical differences of devices was conducted. The technical specifications of devices differ significantly, particularly in relation to viewing virtual content through VR glasses or monitors. VR glasses allow for 360°

viewing through head movements, resulting in a immersive experience (Kronqvist et al., 2016).

Although many VR glasses are already in use for business or private purposes, virtual content is predominantly viewed through monitors; this can be deduced from global sales statistics showing that only 9.9 million AR and VR devices were sold in 2021 (TrendForce, 2022) compared to 144 million PC monitors (IDC, 2022). Though millions of VR glasses are sold, this does not imply that they will be used for virtual events. Video games remain key to the usage of VR glasses, but in a survey of 4,000 US gamers, 60% reported participating in non-gaming activities or events within video games in 2021 (Activate Consulting, 2022).

All devices have technical limitations that affect and restrict the visual display of virtual content. Even in the case of monitors, which are currently widespread in daily practice, there are notable differences (see Table 16). For example, screen size, brightness, resolution, and many other specifications can affect visual perception of virtual content.

Table 16

Technical specifications of monitors affect visual perception

Category	Popular types and value ranges
Aspect ratio	4:3, 16:9, 21:9, 9:16, etc.
Backlight technology	LCD, LED, QLED, OLED, QD-OLED, AMOLED, EDGE-LED, Direct-LED, etc.
Brightness	150 - 1.000 NITs or cd/m^2
Color space	sRGB, DCI-P3, Adobe RGB, etc.
Contrast ratio	1000:1, 5000:1, 10000:1, etc.
Curvature	1800R – 4000R
Drivers and software	Graphic drivers, Browser, Settings in Operating System, etc.
Dynamic range	Non-HDR, HDR, HDR10, HDR10+, etc.
Frame/refresh rate	60Hz, 100Hz, 120Hz, 144Hz, 240Hz, etc.
Glare type	glare, non-glare
Panel type	Twisted Nematics (TN), In Plane Switching (IPS), Patterned Vertical Alignment (PVA), Multi-Domain Vertical Alignment (MVA)
Resolution	1280 × 720 Pixel (HD), 1.920 x 1.080 Pixel (FHD), 3840 x 2160 Pixel (UHD / 4K), 7680 x 4320 Pixel (8K), etc.
Response time	0.5 – 20 ms.
Screen size	14 Inch (in), 15.6 in, 17 in, 19 in, 23 in, 24 in, 27 in, 32 in, 38 in, 43 in, etc.
Viewing angle	120° – 178° (horizontal) 15° – 60° (vertical)

Note. This data corresponds to the contemporary state of monitors available on the commercial market and may deviate due to technical advancements. This information was obtained by the author.

11.4 Discussion

11.4.1 Lack of standardized instruments and scales

The literature review demonstrates that there is a wide range of research approaches for studying the psychological effects of lighting. One challenge to consider is the lack of standardization in measurement instruments

Many instruments use a semantic differential scale but differ in the level and polarity of scaling and the number of items used. For example, Zimmons (2004), Newsham et al. (2010), and Canazei et al. (2016) assess pleasantness. However, the construct of “pleasantness” is not explicitly defined in the individual studies. Therefore, these experimenters assume that “pleasantness” is an intuitive known construct by all subjects.

All three studies used the identical bipolar terms pleasant-unpleasant for rating, but Canazei et al. (2016) use a 4-point scale, Zimmons (2004) use a 7-point Likert scale, Newsham et al. (2010) use a VAS with ratings from 0 – 100.

Initially, these aspects limit the direct comparability of study results. In addition, it is also difficult to assess which scaling is most suitable, though there are arguments in the literature for a 7-point scale. Indeed, in 1924 Symonds suggested that 7-point scales have a high reliability, and Miller (1956) corroborates this with the assumption that the human mind is capable of distinguishing seven different items. A comprehensive literature review and research by Preston and Colman (2000) also concluded that 7-point, 9-point, or 10-point scales are generally preferable.

Constructs and scales that are expected to be difficult for all subjects to understand should be defined and explained to avoid scoring inaccuracies. Such a procedure ensures the overall quality of a study.

Following Churchill (1979), who in the 1970s demanded critical reflection on current marketing research methods and a stronger consideration of validity and reliability in measurement instruments, the discussion of quality criteria will also be appropriate for this area of research.

Churchill (1979) postulated a paradigm of the following eight-step procedure for developing measurement methods:

(1) Specify domain of construct

(2) Generate sample of items

(3) Collect data

(4) Purify measure

(5) Collect data

(6) Assess reliability

(7) Assess validity

(8) Develop norms

Such a structured procedure or at least another transparent process should be documented and be comprehensible for a valid and reliable instrument.

Most of the reviewed studies are based directly or indirectly on the previous research, scales and items of Flynn (Flynn et al., 1973; Flynn et al., 1979; Flynn & Spencer, 1977). Despite this same fundament, no standardized questionnaire can be identified. This finding is consistent with the review of 68 lighting studies by Kong et al. (2022), which was published after the completion of the present study. With each adaptation, there may be changes in procedure, item design, and number of items that may affect the quality of the studies. This finding is in line with Allan et al. (2019), who argue for more consistency in subjective assessments of light quality.

While standardized and well-validated scales and inventories exist for certain constructs in psychology, this should also be strived for in application-oriented research; Especially in the forward-looking research area of virtual environments and Metaverse platforms.

The transfer of psychological measurement methods from physical to virtual environments requires a scientifically coherent investigation considering and reflecting on existing methods and findings. This is a prerequisite for providing scientifically based recommendations for design implementations to improve virtual spaces.

11.4.2 Validity of study designs related to usage behavior and used devices

In current application areas, virtual events such as trade shows are often attended through monitor devices rather than VR glasses. Therefore, for a biotic and valid measurement the device used must be considered in the study design. Watching content on a monitor compared to viewing via opaque VR glasses implies disruptive effects due to the lighting conditions in the physical surroundings. Looking at a screen are accompanied by interfering variables such as distraction by other activities, interrupted eye contact with the monitor, and so on. Even if these interfering variables do not manifest in VR, other issues such as motion sickness may occur (E. Chang et al., 2020).

To be able to examine the psychological effects of virtual spaces as a dependent variable, these interfering variables should ideally be eliminated or at least controlled. Related to validity, these inherent limitations of studies in virtual environments need to be critically reflected upon and discussed.

Psychological insights and technical developments are mutually dependent in virtual environments. There is a wide range of technical parameters in which obligatory devices like VR headsets or monitors differ from one another, potentially affecting individual perception and consequently affecting study results. Technical limitations also determine viable options for improving user experience. As a result, it may not be technologically feasible to implement findings from psychological research, or else technological advances may precede psychological studies.

11.5 Conclusion

The aspects discussed above showcase the complexity of studying and improving virtual spaces. Various challenges become apparent when transferring psychological measurement methods from physical to virtual environments.

Due to these limitations and challenges, the implementation of scientific findings must be conducted carefully. Improvements in the design of virtual spaces based on psychological mechanisms are further affected and limited by technical specifications and usage behaviors. Therefore, the validity and transferability of research findings in this field must be critically observed and reflected upon.

Interdisciplinary research approaches, solutions, and synergies from psychology, perception research, information technologies, design, and human-centered event management must be developed. A prerequisite for improving experiences in virtual spaces and in the Metaverse is understanding psychological mechanisms and considering interdisciplinary scientific findings in the design of these spaces. Improving the user experience of virtual events will be a joint task for science and practice.

12. Study 4 (VL1): Exploring effects of lighting in virtual spaces on perception and quality of stay in biotic environment

12.1 Introduction

The visual perception of spaces, whether in physical or virtual space, requires visual radiation as a stimulus. In the physical environment, approaches such as human-centric lighting and integrative lighting have been established that consider not only a visual but also a non-visual effect of lighting conditions. The increasing popularity of virtual spaces, from simple display applications – as in computer games – to immersive worlds and Metaverse environments that can be entered via HMD, raises special issues. For example, it is necessary to investigate the extent to which the effects of lighting in the physical world apply in virtual spaces. Subsequently, questions also arise regarding the extent to which the measurement instruments of such subjective effects from physical lighting research can be applied in virtual space and whether human-centric lighting in virtual spaces is relevant to user experience and the design of future Metaverses.

The following study in a biotic setting uses Flynn´s et al. (1979) established semantic differential scale to investigate the extent to which color temperature and the influence of virtual daylight affects the evaluation of virtual spaces.

12.2 Participants

The experiment was conducted with 95 participants (48 males, 47 females, $M = 29.79$ years, $SD = 10.75$ years). The participants were recruited through social media and on a German university campus. Participation was voluntary and without payment. There were no language requirements as long as the participants understood the instructions and questions in English. They were naïve to the concrete hypotheses of the study but were informed of the general purpose to investigate virtual lighting. All participants reported normal or corrected-to-normal vision. The participants provided informed consent in accordance with the policies of the University Committee for the Protection of Human Subjects. The experimental protocol was reviewed and approved by the ethics committee of the university.

There were only a few specific subject selection criteria to capture a cross-societal group of participants. An age range of at least 18 years to a maximum of 65 years was established to represent the usual spectrum of people in education or working. Data was collected from participants of 22 nationalities within the age range from 20 to 58 years. The inherent limitations of a heterogeneous group of participants are discussed in Section 12.6.2.

A priori power analysis was performed using G*Power version 3.1.9.7 (Faul et al., 2007) to determine the minimum sample size required to test the study hypothesis. Results indicated that the required sample size to achieve a power level of 95% for detecting a medium effect ($d_z = 0.35$) at a significance criterion of $\alpha = .05$ was $N = 90$ for the paired-t test. The effect size $d_z = 0.35$ has been adopted in previous light studies and has a moderate to small effect. Thus, the obtained sample size of $N = 95$ is more than adequate for a paired t-test. In case of a non-parametric distribution of data, a Wilcoxon signed-ranked test was performed instead of a paired t-test, with an calculated adequate sample size of $N = 94$ ($\alpha = .05$, $d_z = 0.35$). Reducing the power of separation to the common level of 80% while holding $\alpha = .05$ and $d_z = 0.35$ constant, would significantly lower the required sample size to $N = 85$ for the paired *t*-test and $N = 55$ for the Wilcoxon signed-rank test. Hence, a sample size of $N = 95$ is more than sufficient for this type of study.

12.3 Measures

Flynn´s et al. (1979) semantic differential scale, which has been adapted for several lighting research studies (Canazei et al., 2016; Cetegen, Veitch, & Newsham, 2008; Mahdavi & Eissa, 2002), was used to assess participants' perceptions of pictures. The scale consisted of 13 items, each with 7-point Likert scale. The Likert scale is presented in a bipolar scale from -3 to 3 moving from "Very Strongly" on the left quality (-3) to "Very Strongly" on the right quality (3), with 0 being "Neutral." There are 12 pictures in total, which are divided into six pictures in each condition. The pictures were shown in a randomized sequence. The data was analyzed using a pairwise comparison to compare the Likert rating between the lighting conditions of warm/cold lighting and daylight/room lighting.

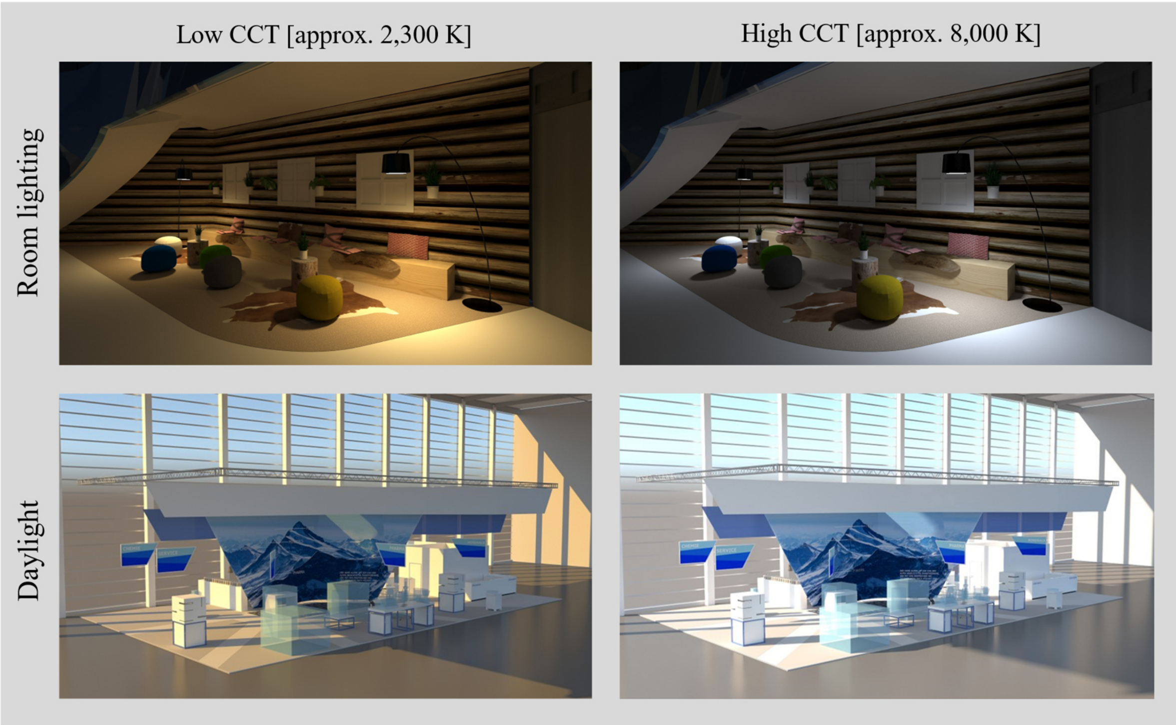
To determine the appropriate statistical test for each comparison, the Shapiro-Wilk test was used to verify that the data met the assumptions of normality (see Table A30). As the situation mandated it, a paired *t*-test (parametric) or a Wilcoxon signed-rank test (non-parametric) was performed. To control for type I error rate, the Bonferroni correction was applied to the analyses. The Bonferroni correction adjusts the significance level for multiple comparisons, ensuring that the overall type I error rate does not exceed a preset alpha level. Effect sizes were either reported as Cohen's *d*, in case of the *t*-test (Cohen, 1988), or Pearson's correlation coefficient *r,* for the Wilcoxon signed-rank (Fritz et al., 2012) and interpreted according to the guidelines in Cohen (1988). Due to the standardized procedure for Likert scales, potential outliers are not assumed to be due to measurement errors or data entry errors. According to Salkind (2010, p. 980), only "if the researcher has reason to believe that an outlier is due to subject or experimenter error, he or she is justified in removing the observation from the data”. Therefore, no data were removed from the analysis or post-processed by winsorizing or trimming.

12.4 Procedure and materials

Subjects were given access to a browser-based online survey via a hyperlink. The study design therefore permitted the experiment to be conducted within the participants' biotic environment, just as they would enter a virtual space with their individual device via a two-dimensional display from their private or work-related environment. After a mandatory informed consent form with instructions and notes on the study, participants had to explicitly agree to participate. Before the start of the stimulus presentation, demographic data, which included age, sex, and nationality, was collected. Subjects were shown a rendering of a virtual space with the following instruction: "Look closely at each of the images and rate how strongly each description makes you feel. You may not skip any question or go back to the previous question." Below the image, the 13 semantic differential items were presented, each with a 7-point rating scale. Twelve stimuli images were shown in randomized sequence for rating (for examples, see Fig. 11). The stimuli were static pictures of virtual spaces used in business applications. Finally, the subjects were thanked for their participation. Total participation lasted about 20 minutes on average.

Figure 11

Examples of stimuli renderings



Note. Created in cooperation with *mac brand spaces GmbH*.

12.5 Results

Beauty

There was no difference in the evaluation of beauty in virtual warm or cold lighting conditions, $t(94) = 1.442$, $p = .153$, $d = 0.148$. The evaluation of beauty of the presented rendering tend significantly to beautiful in virtual spaces with virtual daylight ($t(94) = 3.009$, $p = .003$, $d = 0.309$). The mean value rated from beauty to ugly increased from 0.628 ($SD = 0.90$) in virtual daylight to 0.935 ($SD = 0.87$) in room lighting.

Brightness

Warm lighting ($M = -0.15$, $SD = 0.78$) was rated brighter than cold lighting ($M = 0.868$, $SD = 0.67$), $t(94) = 10.466$, $p < .001$, $d = 1.074$. Hence, daylight ($M = -0.517$, $SD =$

0.71) was rated brighter than room lighting (*M* = 1.124, *SD* = 0.72), $t(94) = 18.820$, $p < .001$, $d = 1.931$.

Clutter

Perception of the stimuli was rated as less cluttered in cold lighting (*M* = -0,618, *SD* = 0.98) than in warm lighting (*M* =-0.342, *SD* = 0.84), $t(94) = -4.001$, $p < .001$, $d = -0.411$. Between daylight (*M* = -0.656, *SD* = 1.06) and room lighting (*M* = -0.453, *SD* = 0.92), there was a difference at a weak level $t(94) = 2.597$, $p < .011$, $d = 0.266$).

Glare

There was no difference in evaluation of glare in virtual warm or cold lighting conditions ($t(94) = 0.958$, $p = .340$, $d = 0.920$). Glare ratings were significantly higher in virtual spaces with virtual room light, $t(94) = -6.326$, $p < .001$, $d = -0.649$. The mean value in a rating differs from glare in room light -.270 (*SD* = 1.08) to non-glare in virtual daylight .473 (*SD* = 0.99).

Hazy

There was no difference in evaluations on the scale from hazy to clear in warm or cold conditions ($t(94) = -1.792$, $p = .076$, $d = .184$). Daylight (*M* = 1.19, *SD* = 0.82) was rated as clearer than room lighting (*M* = 0.401, *SD* = 0.97), $t(94) = 6.030$, $p < .001$, $d = -0.619$.

Likeability

There was no difference in evaluation of likeability in warm or cold conditions ($t(94) = -0.037$, $p = .970$, $d = -0.004$). Daylight (*M* = 0.7982, *SD* = 0.85) was rated more likelable than room lighting (*M* = 0.416, *SD* = 0.85), $t(94) = -4.292$, $p < .001$, $d = -0.435$.

Pleasantness

There was no difference in the evaluation of pleasantness in warm or cold conditions ($t(94) = -1.494$, $p = .138$, $d = .153$). Daylight ($M = 0.780$, $SD = 0.92$) was rated as less pleasant than room lighting ($M = 0.335$, $SD = 0.80$), $t(94) = 5.218$, $p < .001$, $d = 0.535$.

Privacy

A Wilcoxon signed-rank test showed a statistically significant difference (-0.833) in reported privateness in cold lighting condition ($Mdn = 1.167$) compared to warm lighting conditions ($Mdn = 0.333$), $z = -5.840$, $p < .001$, $r = .60$. Daylight ($M = 1.189$, $SD = 0.82$) was rated as more private than room lighting ($M = 0.496$, $SD = 0.92$), $t(94) = -7.829$, $p < .001$, $d = -0.803$.

Relaxation

A Wilcoxon signed-rank test showed a statistically weak significant difference in reported relaxation in cold lighting conditions ($Mdn = 0.333$) compared to warm lighting conditions ($Mdn = 0.167$), $z = -2.195$, $p < .028$, $r = .225$). Daylight ($M = 0.426$, $SD = 0.81$) was rated as more tense ($M = 0.144$, $SD = 0.75$) than room lighting ($t(94) = -3.216$, $p = .002$, $d = -0.330$).

Stimulation

Cold lighting ($M = 0.208$, $SD = 0.69$) was rated as more stimulating than warm lighting ($M = 0.486$, $SD = 0.71$), $t(94) = -3.387$, $p < .001$, $d = -0.347$. Daylight ($M = 0.068$, $SD = 0.69$) was rated as more stimulating than room lighting ($M = 0.626$, $SD = 0.80$), $t(94) = 5.667$, $p < .001$, $d = 0.581$.

Specialty

There was no difference in evaluation from ordinary to specialty in warm or cold conditions ($t(94) = -0.596$, $p = .553$, $d = -0.061$). Daylight ($M = 0.170$, $SD = 0.84$) was rated as more ordinary than room lighting ($M = 0.511$, $SD = 0.75$), $t(94) = 3.629$, $p < .001$, $d = 0.918$.

Spaciousness

A Wilcoxon signed-rank test showed a statistically significant difference (0.666) in reported spaciousness in cold lighting conditions ($Mdn = 0.833$) compared to warm lighting conditions ($Mdn = 0.167$), $z = -6.776$, $p < .001$, $r = .695$. Spaciousness was significantly higher in virtual spaces with virtual daylight than in room lighting, $t(94) = -5.479$, $p < .001$, $d = 0.562$. The mean value of the spatiality (Spaciousness) rating in room lighting 0.184 ($SD = 1.03$) increased to 0.735 ($SD = 0.91$) in virtual daylight.

Visual temperature

Visual temperature was correspondingly rated to the presented stimuli and was significantly cooler in cold lighting conditions, ($t(94) = -8.966$, $p < .001$, $d = 0.920$). The mean values differ by 1.176 rating points from warm conditions ($M = -.433$, $SD = .96$) to cold conditions ($M = 0.743$, $SD = 0.77$). There was a weak significant difference in the evaluation of visual temperature in virtual room or daylight conditions ($t(94) = -2.290$, $p = .024$, $d = -0.235$).

12.6 Discussion

12.6.1 Effects of virtual lighting

Effects of CCT

The identified large effects ($|d| > 0.8$) in visual assessment of brightness and perceived CCT are in line with expectations. Above all, this confirms that the stimuli were actually perceived as visually warm or cold by the subjects according to the preselection of the experimenters. Medium effects ($0.2 < |d| < 0.8$) were found in the evaluation of cluttering and stimulation; this is in line with current studies from the physical environment, which attribute a stimulating effect to high CCT illumination.

Regarding VR environments these findings fit into the framework of a study by Llinares et al. (2021), who found differences in attendance and memory performance as well as neurological responses induced by different CCT settings in a virtual classroom. Analyses of heart rate variability (HRV) indicated that cold-hued spaces generated greater sympathetic activity and less parasympathetic activity and are thus associated with an increase in arousal. The EEG results also suggested that cold-hued spaces contribute to the achievement of higher levels of attention and cognitive performance (Llinares et al., 2021).

For the nonparametric items, cold light also seemed to be associated with spaciousness; this is consistent with assumptions that cold lighting is more likely to occur in spacious environments, such as learning and work environments, instead of private or relaxing spaces. Previous studies on physical spaces indicated that people have a certain expectation of spaces and their CCT levels due to “conceptual lighting” (see Section 9.2).

Effects of virtual daylight

Spaces with virtual daylight were perceived as brighter and more private than spaces with room lighting, with a large effect ($|d| > 0.8$). Medium effects ($0.2 < |d| < 0.8$) indicate that spaces with virtual daylight are rated as brighter, clearer, more stimulating, more generous, more glaring, more private, and more beautiful. These various positive effects are in line with findings of positive effects from physical lighting research. Haans (2014) concluded after several sequential studies that people have a natural appraisal for daylight rather than electric light; this is consistent with various studies conducted in the 1990s (Veitch et al., 1993;

Veitch & Gifford, 1996) and more recently (Heydarian et al., 2016; Heydarian et al., 2017; Mahmoudzadeh et al., 2021).

Beute and Kort (2013) found a robust preference for natural, bright, and sunny scenes but no implicit preference for the separated factors of nature, brightness, or sunlight. Due to various positive effects, the use of artificial skylights is also a field of research for physical rooms (Canazei et al., 2016; Kahn et al., 2008; Mangkuto et al., 2014; Seuntiens et al., 2012). It is thus reasonable to assume that virtual daylight also takes on a significant role in virtual spaces. Hegazy et al. (2021) finds a strong consistency between perceptions of daylight in real and virtual environments.

When considering warm and cool lighting settings, four significant differences ($p < 0.05$) with at least medium effect sizes ($|d| > 0.2$) were found, whereas there were 12 significant differences when evaluating daylight and non-daylight settings. Thus, the simulated type of light source appears to be a relevant influencing factor in the evaluation of virtual environments. However, especially with respect to the emerging Metaverse concept, no literature adequately addresses the role of virtual daylight in immersive worlds. Existing literature on virtual and simulated daylight mainly focuses on how it is used in architecture, computer science, lighting, and psychological research as a planning tool or as an alternative research method to replace studies in real environments. The particular role of virtual and simulated daylight in the design of virtual environments and Metaverses for business, learning, or entertainment purposes has not been sufficiently addressed. However, past research findings as well as this study indicate that human-centered lighting for virtual spaces and Metaverse is necessary.

12.6.2 Limitations

This study took place within the biotic environments of participants, which carries both advantages and disadvantages. On the one hand, this environment corresponds most closely to what the real situation and behaviors of subjects would be if they were to participate in virtual spaces. On the other hand, this setting comprises uncontrollable confounding variables. Because of these variables, other influences the person is exposed to before or during the survey cannot be traced. The present study investigated the subjective evaluation of a spatial perception, and there are no indications that, for example, current emotional states would have a direct effect on this evaluation, as would be the case with a survey of emotional-affective variables. However, it cannot be excluded that locally existing external multisensory influences and a multimodal perception through sounds, haptic, visual, and olfactory influences could have an influence on the evaluation of the presented spaces (Nidiffer et al., 2016; Spence, 2020). . For example, a prolonged stay in a closed and dark physical room could lead to a biased positive evaluation of virtual spaces with virtual daylight. Conversely, an evaluation of virtual spaces while being exposed to direct sunlight and thermal heat could promote subconscious preferences for spaces associated with shade and coolness. The relationships between visual and thermal perception have already been corroborated (Huebner et al., 2016; Salamone et al., 2020; Winzen et al., 2014).

Another aspect of the biotic situation was that the subjects were able to use their everyday devices, resulting in heterogeneity in the technical specifications of the devices used in each case, such as brightness, resolution, color rendering, and so on. However, this variability also occurs among real-world end users of commercial virtual environments. This aspect was therefore taken into account and investigated in more detail in a further controlled study with identical devices (see VL2, Chapter 13).

In the present study, the stimuli were chosen to resemble actual applications in everyday work as closely as possible. To achieve this, virtual renderings were taken, which are commonly used in the meeting and trade fair business (allseated ExVo and mac brand spaces). This limited the freedom of design for research parameters such as CCT and spatial design, but it allowed research on real-world stimuli that are already common in the practical application of virtual platforms. Care was taken to present identical situations with perceptible differences in CCT, which was successfully confirmed by the results.

According to and Engelke et al. (2013), and Yilmaz (2018), "[…] computer-based visualisations convey statistically similar lighting perception as in a real-world scenario" (Yilmaz, 2018, p. 159). Nevertheless, displaying static screenshots instead of being able to move around in the virtual environment could be a limitation that could influence the subjective ratings of the presented stimuli.

Comparing daylit and non-daylit illuminated virtual spaces is more difficult to study than different CCT conditions. Either virtual sunlight as a light source must be suggested, for example, by comprehensible light radiation through a window in a contained space, or by recognizability of a virtual sky. In the present study, simulations of daylight through windows and visibility of the sky were used. Furthermore, the actual properties of daylight can only be reproduced to a very limited extent due to technical limitations, such as the brightness and spectral distribution of displays. For the purpose of investigating realistic and commercially widespread VR environments, these technical limitations were tolerated.

The limited selection criteria of the sample allowed a heterogeneous distribution of age, sex and nationality. The broad-based study thus also corresponds to a realistic user field of VR applications, which are open to persons of any age and sex from any country. In a controlled follow-up study (VL2), a homogeneous group of German students was surveyed to reduce such potential confounding effects associated with a heterogeneous sample group.

The investigation of interindividual differences would have to include additional sociodemographic variables, which would have to be elaborated in further studies. Recommendations for the future design of virtual spaces in terms of HCL should have general validity and should not be tailored to individual groups. Gender studies already investigate gender differences in the preferences and effects of lighting and space perception (Chellappa et al., 2017; Hartstein et al., 2018; Huang et al., 2020; Knez & Enmarker, 1998; Knez & Kers, 2000; Schweitzer et al., 2016). Marie et al. (2019) found differences in light sensitivity between US and Chinese citizens, but these were not gender-specific. Research of individual factors is correspondingly complex.

12.6.3 Future research

The results demonstrate that virtual daylight can lead to a change in the evaluation of virtual spaces, and this represents an interesting starting point for future research. The conceptual drawbacks of the present biotic survey could be complemented by a more controlled laboratory study. A homogeneous experimental group and identical displays with identical technical characteristics would be appropriate for this purpose, particularly for comparison with these heterogeneous results. A future study should recruit a homogeneous group of undergraduate students using identical devices in a controlled environment.

12.7 Conclusion

The transfer of measurement methods from physical light research to virtual light research works. The results partly coincide with expectations and prior knowledge from the physical world and have implications for the design of human-centered virtual environments. Notably, the perception of high and low CCT values as cold or warm also occurs in virtual spaces. Similarly, the stimulating effect of cold lighting also seems to occur in virtual environments. The simulation of daylight can contribute to an atmosphere that is perceived as brighter, clearer, more stimulating, more generous, more glaring, more private, and more beautiful. The role of virtual daylight in virtual spaces therefore represents a particularly interesting area of investigation from a psychological, technological, design, and user-oriented perspective.

13. Study 5 (VL2): Exploring effects of lighting in virtual spaces on perception and quality of stay in laboratory environment

13.1 Participants

Previous research has demonstrated that effect sizes can be considered medium to large. The analysis of 17 paired *t*-tests in the previous study revealed an average effect size of $d = 0.45$ ($SD = 1.54$). An a priori power analysis using G*power 3.1.9.7 (Faul et al., 2007) indicates that a sample size of 55 subjects would suffice to achieve a power level of 0.95. Nonparametric Wilcoxon signed-rank tests yielded even higher effect sizes, with an average of $r = .76$ ($SD = 0.07$). Thus, it can be assumed that 58 subjects would be a sufficient minimum sample size. To ensure this study's quality and the ability to detect potentially smaller effects, a sample of 106 subjects was ultimately included to make the study robust to outliers.

Of the 106 participants, 104 were German citizens, and two had Italian and French citizenship, respectively, but were raised and live in Germany and were therefore included in the study. The sample was balanced at 53 male and 53 female participants. The age of the participants ranged from 18 to 26 years, with a mean age of 21.17 ($SD = 1.70$), and was therefore homogeneous. All participants were undergraduate students in a bachelor's degree program in business administration and were also homogeneous with respect to educational background. The participants provided informed consent in accordance with the policies of the University Committee for the Protection of Human Subjects. Participation was voluntary and without payment. All participants reported normal or corrected-to-normal vision.

13.2 Measures

Depending on the parametric tested by a Shapiro-Wilk test (see Table A31), a paired *t*-test (parametric) or a Wilcoxon signed-rank test (non-parametric) was performed. Bonferroni correction was applied to the analyzed data. To report the effect size, Cohen's *d* was calculated for the *t*-test (Cohen, 1988), while Pearson's correlation coefficient *r* was used for the Wilcoxon signed-rank test (Fritz et al., 2012). The interpretation of the effect sizes was according to Cohen (1988). Due to the standardized procedure in Likert scales, potential outliers are not assumed to be due to measurement errors or data entry errors. According to Salkind (2010) therefore no data were removed from the analysis or post-processed by winsorizing or trimming.

13.3 Procedures and materials

Subjects were led in groups of up to 30 to an experimental room with 32 identical PC setups available (see below for details). Each person was placed at a personal computer (PC) with a mouse and keyboard. A browser-based survey was displayed on each monitor. After a mandatory informed consent form with instructions and notes on the study, participants had to explicitly agree to participate. Before the start of the stimulus presentation, demographic data, which included age, sex, and nationality, was collected. Subjects were shown a screenshot from a virtual space with the following instruction: "Look closely at each of the images and rate how strongly each description makes you feel. You may not skip any question or go back to the previous question." Below the image, the 13 semantic differential items were presented, each with a 7-point rating scale. Twelve stimuli images were shown in a randomized sequence for rating. The stimuli were static pictures of virtual spaces used in business applications. Subsequently, eight items were used to elicit general personal preferences about lighting and environmental factors such as simulated times of day and simulated weather in virtual spaces. The participants could indicate their preference on a bipolar 7-point rating scale (-3 to +3). Finally, the subjects were thanked for their participation. Total participation lasted about 20 minutes on average.

In this study, 32 LG Flatron IPS231PX LED-backlit monitors were utilized to present stimuli to participants. Each monitor was equipped with a 23-inch IPS screen displaying a pixel resolution of 1920x1080, RGB and sRGB color space, with a brightness of 250 cd/m², a frame rate of 60 Hz, a contrast ratio of 1000:1, and a 178° viewing angle. All monitors were run at their color-adjusted factory default settings and were adjusted to the individual viewing height of each participant for optimal visibility. The computers used to run the stimuli were identical and equipped with Intel Core i5-6500T processors clocked at 2.50 GHz, Intel Graphics 530 graphics cards, and 64-Bit Windows 10 Enterprise operating systems.

To control for environmental factors, the air temperature in the testing room was kept at a constant 20° Celsius (+/-0.5°) throughout the experiment, and daylight was blocked out by shutters. LED ceiling lighting with a color temperature of 3,835 K, a CRI [R_a] of 81, an intensity of 1,020 lx on desktop surface, an alpha peak of 595 nm, and a flicker index < 0.05 was maintained to illuminate the 9.20 x 7.85 m room with white walls.

The standardized monitors and environmental controls aimed to reduce variability and ensure the accuracy and reliability of the results.

13.4 Results

Beauty

A Wilcoxon signed-rank test statistically demonstrated that warm lighting was rated as more beautiful (*Mdn* = -1.166) than cold lighting (*Mdn* = -0.167), with a significant difference (z = 7.366, p < .001, r = .72). Similarly, virtual daylight (*Mdn* = -1.583) was rated as more beautiful than room lighting (*Mdn* = -0.167), with a statistically significant difference (z = 8.105, p < .001, r = .79).

Brightness

Cold lighting (M = -1.487, SD = 0.99) was rated as brighter than warm lighting (M = -0.756, SD = 0.78), t(105) = 21.009, p < .001, d = 2.041. Daylight (M = -1.168, SD = 0.93) was rated as brighter than room lighting (*M* = -0.437, *SD* = 0.76), $t(105) = 17.016$, $p < .001$, $d = 1.653$.

Clutter

The stimuli was rated as less cluttered in cold lighting (*M* = 0.967, *SD* = 0.869) than warm lighting (*M* = 0.248, *SD* = 0.74), $t(105) = -7.342$, $p < .001$, $d = 0.713$. Between daylight (*M* = 0.755, *SD* = 0.85) and room lighting (*M* = 0.460, *SD* = 0.64) there was a significant difference, $t(105) = -3.734$, $p < .001$, $d = 0.363$. Daylight was rated as less cluttered.

Glare

Cold lighting was rated as having more glare (*Mdn* = -0.333) than warm lighting (*Mdn* = 1.500), with a statistically significant difference ($z = 7.949$, $p < .001$, $r = .77$). Additionally, virtual daylight (*M* = 0.351, *SD* = 0.918) was rated as having more glare than room lighting (*M* = 0.626, *SD* = 0.722), with a statistically significant difference ($t(105) = 2.831$, $p = .006$, $d = 0.275$).

Hazy

Warm lighting was rated as much hazier (*Mdn* = -1.583) than cold lighting (*Mdn* = 1.916), with a statistically significant difference ($z = -8.535$, $p < .001$, $r = .83$). Room lighting (*M* = 0.423, *SD* = 0.65) was rated as hazier than daylight (*M* = 1.156, *SD* = 0.64), with a statistically significant difference ($t(105) = 9.505$, $p < .001$, $d = 0.923$).

Likeability

Warm lighting was liked (*Mdn* = 1.500) more than cold lighting (*Mdn* = 0.167), $z = 7.189$, $p < .001$, $r = .70$). Daylight lighting was liked (*Mdn* = 1.500) more than cold lighting (*Mdn* = 0.167), $z = -7.964$, $p < .001$, $r = .77$.

Pleasantness

Warm lighting was rated as more pleasant (*Mdn* = -1.583) than cold lighting (*Mdn* = 0.000), $z = -7.780$, $p < .001$, $r = .76$. Daylight lighting was rated as more pleasant (*Mdn* = -1.333) than room lighting (*Mdn* = -0.167), $z = -7.438$, $p < .001$, $r = .72$.

Privacy

A Wilcoxon signed-rank test showed a statistically significant difference in reported privateness in cold lighting conditions (*Mdn* = -2.000) compared to warm lighting conditions (*Mdn* = 1.000), $z = -8.826$, $p < .001$, $r = .86$. Room lighting ($M = -0.109$, $SD = 0.64$) was rated as more private than daylight ($M = -0.816$, $SD = 0.64$), $t(105) = 10.020$, $p < .001$, $d = 0.973$.

Relaxation

A Wilcoxon signed-rank test showed a statistically significant difference in reported relaxation ratings in cold lighting conditions (*Mdn* = 1.667) compared to warm lighting conditions (*Mdn* = -1.583), $z = 2.195$, $p < .001$, $r = .71$. There was no significant difference ($p = .053$) in the evaluation of relaxation and tenseness in virtual room lighting or daylight conditions.

Spaciousness

A Wilcoxon signed-rank test showed a statistically significant difference (1.667) in reported spaciousness for cold lighting conditions (*Mdn* = 1.167) compared to warm lighting conditions (*Mdn* = 0.500), $z = 8.826$, $p < .001$, $r = .71$. Daylight was rated as more spacious (*Mdn* = 1.333) than room lighting (*Mdn* = -0.500), $z = -7.197$, $p < .001$, $r = .70$.

Stimulation

Cold lighting (*Mdn* = -1.500) was rated as more stimulating than warm lighting (*Mdn* = 0.417), $z = 5.913$, $p < .001$, $r = .57$. Daylight ($M = -0.566$, $SD = 0.54$) was rated as more stimulating than room lighting ($M = -0.189$, $SD = 0.763$), $t(105) = 4.906$, $p < .001$, $d = 0.477$.

Specialty

Cold ($M = 0.124$, $SD = 0.71$) was rated as more ordinary than warm lighting ($M = 0.662$, $SD = 0.645$), $t(105) = 8.066$, $p < .001$, $d = 0.783$. Daylight ($M = 0.223$, $SD = 0.75$) was rated as more ordinary than room lighting ($M = 0.563$, $SD = 0.63$), $t(105) = 4.715$, $p < .001$, $d = 0.458$.

Visual temperature

Visual temperature was rated as significantly cooler in cold lighting conditions (*Mdn* = 2.167) than in warm lighting conditions (*Mdn* = -2.083), with a statistically significant difference ($z = -8.748$, $p < .001$, $r = .85$). However, there was no significant difference ($p > .776$) in the evaluation of visual temperature in virtual room lighting or daylight conditions.

Preferences

Table 17 provides a comprehensive overview of the descriptive statistics and distribution of the data. Mean, median, and mode are measures of central tendency of the responses to the survey items about preferences in virtual spaces. For example, indicated by the positive measures, participants clearly preferred daylight rather no daylight in virtual spaces ($M = 2.21$, *Mdn* = 3, *Mo = 3, SD = 1.22)*.

Table 17

Descriptive statistics for preferences in virtual spaces

Item	*N*	*M*	*Mdn*	*Mo*	*SD*
No shadows / shadows	106	1.21	1	2	1.41
Ceiling above / sky above	106	1.67	3	3	1.80
No daylight / daylight	106	2.21	3	3	1.22
No local daylight / local daylight	106	-0.88	-1	-2	1.85
No weather / weather simulation	106	1.67	2	3	1.72
No local weather / local weather simulation	106	-1.26	-2	-3	1.73
Cloudy sky / sunny sky	106	2.10	3	3	1.32
No realistic lighting / realistic lighting	106	2.06	2	3	1.19

The frequency distribution of the survey responses is provided in detail below and can be found in Table A32. This table presents a comprehensive overview of the distribution of responses to the survey items on preferences in virtual spaces, including the frequency of each response and the percentage of participants who chose each option.

A total of 79.2% of the subjects generally preferred the lighting in virtual environments to cast shadows. 9.4% felt neutral, and 11.3% preferred no shadows (M = 1.21, SD = 1.41).

A total of 72.6% of participants generally preferred an open sky to closed ceilings in virtual spaces (M = 1.67, SD = 1.80), with more than half (52.8%) indicating that they “prefer [open sky] very strongly (+3)." In contrast, 12.3% felt neutral, and 15.1% preferred a closed ceiling.

A total of 90.6% of participants generally preferred virtual daylight in virtual spaces (M = 2.21, SD = 1.21), while 3.8% felt neutral and 5.6% rejected it.

A total of 25.5% of participants preferred simulated daylight in virtual environments that reflects the local daylight conditions (M = -0.88, SD = 1.85), 9.4% felt neutral, and the majority (65.1%) disliked simulated local conditions.

A total of 78.3% of participants preferred virtual weather conditions in virtual environments (M = 1.67, SD = 1.72), 3.8% were neutral, and 18.0% reject virtual weather.

A total of 16.9% of participants preferred simulated weather in virtual environments that reflects local weather conditions (M = -1.26, SD = 1.73), 15.1% were neutral, and the majority (68.0%) reject simulated local weather conditions.

A total of 83.0% of subjects preferred sunny rather than cloudy skies in virtual environments (M = 2.10, SD = 1.32), 12.3% felt neutral, and a minority (4.6%) preferred cloudy skies.

A total of 89.6% of subjects preferred realistic lighting conditions in virtual environments (M = 2.06, SD = 1.19), 5.7% felt neutral, and the minority (4.7%) preferred unrealistic lighting conditions.

13.5 Discussion

13.5.1 Effects of virtual lighting and preferences

In summary, the study found that warm lighting was rated as more beautiful, less glaring, more likeable, more pleasant, and less hazy compared to cold lighting. Virtual daylight was also rated as more beautiful and less glaring than room lighting. For its part, cold lighting was rated as more private and spacious. There was no significant difference in the evaluation of visual temperature or relaxation in virtual room lighting or daylight conditions. Additionally, cold lighting was rated as brighter than warm lighting, and daylight was rated as brighter than room lighting. Overall, the results of the study suggest that warm lighting is preferred over cold lighting in terms of beauty, glare, likeability, pleasantness, and haziness.

The analysis of reported preferences clearly supported that users preferred simulated shadows, open sky instead of ceiling, daylight conditions, virtual weather conditions, sunny sky instead of cloudy sky, and realistic lighting in the virtual space.

These results suggest that virtual spaces use the real physical environment as a benchmark. There is a certain expectation that the laws of physics, such as correct shadow fall and variable lighting conditions, will also apply in the digital realm. Comparable to studies from the physical world, daylight and sunlight are clearly preferred. Simulating the real world with features that provide a certain quality of stay and are typically viewed positively – such as a sunny sky (Beute & Kort, 2013) – should therefore be made an objective when designing virtual spaces.

However, the preference for virtual daylight and weather does not imply that real local daylight and weather conditions should be simulated in the virtual space. Rather, the results indicate that a separation of virtual spaces from the real environment is desirable; this can be interpreted as people wanting to use virtual spaces for positive experiences, with virtual weather conditions that are pleasant. Furthermore, differentiating virtual spaces from one's local environment emphasizes the immersive and experiential nature of virtual worlds, as opposed to simply replicating one's local environment.

13.5.2 Limitations

In this study, all subjects used an identical office PC configuration with a specific monitor type and the same default settings. Besides the manufacturer's specifications, a detailed measurement of the actual display parameters could be made. It cannot be excluded that technical deviations may occur in different production batches or within the lifetime of a monitor. The manufacturing date of the devices is identical, and a similar runtime can be assumed. All devices were calibrated at the beginning of the study and visually checked by the experimenter for identical image reproduction. With additional technical equipment, these individual screen parameters could be recorded and reported upon in more detail.

It is noteworthy that the monitors used in this study are commonly used in practice, making the results relevant to potential users. As technology advances with higher resolutions, more dynamic range and better color rendering, the experience of virtual spaces may become even more immersive. The role of HMDs in future research should be further explored as basic visual perception and assessment may be similar, but technical limitations of image reproduction must also be considered. Additionally, the added complexity of movement through virtual space should be examined in future studies. To minimize the effect of environmental influences, such as temperature change, solar radiation and noise, all participants sat on the same chairs at the same tables, and they were exposed to the same neutral room lighting. However, it is important to consider other inter- and intrapersonal variables such as fatigue, hunger, and emotional states that could influence the assessment.

The study only included undergraduate students between the ages of 18 and 26. Therefore, a fully representative survey of an entire population (e.g., German citizens) cannot be inferred.

13.5.3 Future research

In addition to research on monitors, which are currently still in widespread use, the use of HMDs in future applications and research should also be investigated in more detail. Technical limitations of image rendering also occur and can differ from the screen-based representation of virtual spaces due to their three-dimensional character and motion parameters. Movement through virtual spaces is an additional complexity factor in visual perception studies. The 13 items of Flynn´s semantic differential scale were found to be suitable for transfer to virtual light research, and future studies could address which other instruments are transferable and how corresponding question items could be adapted to future research interests. In addition to the measurement instrument, the independent variables (i.e., visual stimuli) can also be adapted to specific research questions. For example, they can also be differentiated according to the function of the virtual space, such as work or entertainment.

In addition to the dependent and independent variables, the sample can also be varied to account for interpersonal differences of, for example, culture, age, or educational background in subjective evaluations of virtual room lighting.

Future research can provide more detailed results and recommendations for the development of virtual spaces and could include an adaptation of HCL to human-centric virtual lighting (HCVL) that respects the capabilities and limitations of virtual spaces.

13.6 Conclusion

This study explored the effects of virtual lighting in virtual spaces on perception and quality of stay within a homogeneous group of subjects in a laboratory setting. A total of 106 participants, all of whom were undergraduate students in a bachelor's program in business administration, were included in the study. The study used a combination of parametric and non-parametric tests to analyze the data, including *t*-tests and Wilcoxon signed-rank tests. The results of the study revealed that warm lighting was significantly rated as more beautiful, more liked, more pleasant, more hazy, more private, more relaxing, more cluttered, more special, less glaring, less spacious, less bright, less stimulating, and visually warmer than cold lighting. Similarly, virtual daylight was rated as more beautiful, more glaring, more liked, more pleasant, more spacious, more bright, more stimulating, less hazy, less private, less special, and less cluttered than room lighting. These findings suggest that lighting in virtual rooms can have a significant impact on perception and quality of stay. The use of standardized monitors and environmental controls in the study helped to reduce variability and ensure the accuracy and reliability of the results. The analysis of reported preferences clearly showed that users prefer virtual shadows, open sky instead of ceiling, daylight conditions, weather conditions, sunny sky instead of cloudy sky, and realistic lighting in the virtual space.

14. Study 6 (VL3): Comparison of biotic and laboratory study outcomes

14.1 Participants

The aim of this analysis was to examine the level of homogeneity among participants in two separate studies, Study VL1 (N = 95) and Study VL2 (N = 106). The samples in these studies differed in terms of homogeneity: Study VL1 had a broad range of participants, while Study VL2 had a more restricted sample that was limited to a specific age group, nationality, and educational background.

In Study VL2, the age range was 8 years (minimum age 18, maximum age 26), with a mean of 21.2 (SD = 1.70). In contrast, in Study VL1 the age range was 38 years (minimum age 20, maximum age 58), with a mean of 29.76 (SD = 10.75). Both studies had a balanced distribution of male and female participants: Study VL1 had 47 males and 48 females, and Study VL2 had 53 males and 53 females. Study VL1 had participants from 22 countries across all continents, predominantly from India (34.7%) and Malaysia (27.4%). In contrast, Study VL2 had a homogeneous nationality distribution, with participants from three central European countries (104 German citizen, 1 Italian citizen, 1 French citizen), all of whom grew up and live in Germany.

In terms of educational background, participation in Study VL1 did not require a certain educational background, and it was not recorded. In contrast, Study VL2 only included undergraduate students from a bachelor's program in business administration to provide a homogeneous educational background.

14.2 Measures

This study provides a comparative analysis of previously reported findings for Studies VL1 and VL2. The studies' respective results for the 13 items analyzed via a Wilcoxon signed-rank test or paired t-test (depending on parametric or non-parametric distribution) are contrasted and the findings are examined for consistency. Only items that exhibit significant effects (at the $\alpha = .05$ level) in both studies are included in the comparison of direction of effect. Items that show consistent effects in the same direction across both studies are the basis for subsequent modeling using an HCVL approach (see Chapter 15). However, any contradictory results are critically examined and interpreted.

14.3 Procedure and materials

Both studies used the same stimuli pictures, same scales, and same language (English). Whereas in Study VL1 a biotic setting was facilitated by allowing subjects to participate in the study at a freely selectable time and at a freely selectable location on their private device, in Study VL2 many conditions were controlled. Study VL2 was conducted on identical devices in a constantly lit space at constant room temperature. The data available from the two experimental studies was processed in IBM SPSS 28.

14.4 Results

Eleven of 17 significant effects could be confirmed in the same direction. In the case of six effects, contradictory findings were found. The first contradictory results were in the evaluation of glare in relation to room lighting versus daylight. In Study VL1 virtual room lighting was rated as significantly more glaring than daylight, $t(94) = -6.326$, $p < .001$, $d = -0.65$, with a mean difference of $M_{\text{Diff}} = -0.270$ ($SD = 1.08$) between glare in room light to non-glare in virtual daylight ($SD = 0.99$).

In contrast, in Study VL2, daylight ($M = 0.351$, $SD = 0.918$) was rated as more glare than room light ($M = 0.626$, $SD = 0.72$), $t(105) = 2.831$, $p = .006$, $d = 0.28$. Similarly, when assessing the brightness of warm and cold light stimuli, a different result emerged from Study VL1 to Study VL2. In Study VL1, warm light was rated as brighter, $t(94) = 10.466$, $p < .001$,

$d = 1.07$, whereas in Study VL2, cold light was rated as brighter, $t(105) = -21.009$, $p < .001$, $d = 2.04$.

Contradictorily, in Study VL1 cold light was associated with privacy (*Mdn* = 0.333, $z = -5.840$, $p < .001$, $r = .60$, whereas in VL2 warm light was associated with privacy (*Mdn* = 1.000, $z = -8.826$, $p < .001$, $r = .86$). Similarly, there was a switch in the ratings of daylight and room lighting: in VL1, daylight was rated with higher privacy, $t(94) = -7.829$, $p < .001$, $d = -0.803$, whereas in the second study, room lighting was rated as more private, $t(105) = 10.020$, $p < .001$, $d = 0.973$.

The following tables present a comparison of effects observed in Studies VL1 and VL2 in CCT (Table 18) and daylight conditions (Table 19).

Table 18

Comparison of Studies VL1 and VL2 in the independent variable CCT level

Item	VL1 ($N = 95$)	VL2 ($N = 106$)	Comparison of found effects
Beauty	*n. s.*	$z = -7.366$, $p < .001$, $r = .72$	—
Glare	*n. s*	$z = 7.949$, $p < .001$, $r = .77$	—
Visual temperature	$t(94) = -8.966$, $p < .001$, $d = 0.920$	$z = -8.748$, $p < .001$, $r = .85$	consistent
Liking	*n. s.*	$z = -7.189$, $p < .001$, $r = .70$	—
Pleasantness	*n. s.*	$z = -7.780$, $p < .001$, $r = .76$	—
Hazy	*n. s.*	$z = -8.535$, $p < .001$, $r = .83$	—
Privacy	$z = -5.840$, $p < .001$, $r = .60$	$z = 8.826$, $p < .001$, $r = .86$	inconsistent
Spaciousness	$z = -6.776$, $p < .001$, $r = .70$	$z = -8.826$, $p < .001$, $r = .71$	consistent
Relaxation	$z = -2.195$, $p < .028$, $r = .23$	$z = -2.195$, $p < .001$, $r = .71$	consistent
Brightness	$t(94) = 10.466$, $p < .001$, $d = 1.074$	$t(105) = -21.009$, $p < .001$, $d = 2.041$	inconsistent
Stimulation	$t(94) = -3.387$, $p < .001$, $d = -0.347$	$z = -5.913$, $p < .001$, $r = .57$	consistent
Specialty	*n. s.*	$t(105) = -8.066$, $p < .001$, $d = 0.783$	—
Clutter	$t(94) = -4.001$, $p < .001$, $d = -0.411$	$t(105) = 7.342$, $p < .001$, $d = 0.713$	inconsistent

Note. n .s. = not significant

Table 19

Comparison of Studies VL1 and VL2 in the independent variable daylight condition

Item	VL1 ($N = 95$)	VL2 ($N = 106$)	Comparison of found effects
Beauty	$t(94) = 3.009, p = .003, d = 0.309$	$z = 8.105, p < .001, r = .79$	consistent
Glare	$t(94) = -6.326, p < .001, d = 0.649$	$t(105) = 2.831, p < .006, d = 0.275$	inconsistent
Visual temperature	$t(94) = -2.290, p = .024, d = -0.235$	*n. s.*	—
Liking	$t(94) = -4.292, p < .001, d = -0.435$	$z = -7.964, p < .001, r = .77$	consistent
Pleasantness	$t(94) = 5.218, p < .001, d = 0.535.$	$z = -7.438, p < .001, r = .72$	inconsistent
Hazy	$t(94) = 6.030, p < .001, d = -0.619$	$t(105) = 9.505, p < .001, d = 0.923$	consistent
Privacy	$t(94) = -7.829, p < .001, d = -0.803$	$t(105) = 10.020, p < .001, d = 0.973$	inconsistent
Spaciousness	$t(94) = -5.479, p < .001, d = 0.562$	$z = -7.197, p < .001, r = .70$	consistent
Relaxation	$t(94) = -3.216, p = .002, d = -0.330$	*n. s.*	—
Brightness	$t(94) = 18.820, p < .001, d = 1.931$	$t(105) = 17.016, p < .001, d = 1.653$	consistent
Stimulation	$t(94) = 5.667, p < .001, d = 0.581$	$t(105) = 4.906, p < .001, d = 0.477$	consistent
Specialty	$t(94) = 3.629, p < .001, d = 0.918$	$t(105) = 4.715, p < .001, d = 0.458$	consistent
Clutter	*n. s.*	$t(105) = 4.715, p < .001, d = 0.458$	—

Note. n .s. = not significant

14.5 Discussion

The results indicate that cold white lighting was also perceived as visually cold and led to an increased spaciousness rating. Additionally, two non-visual effects were identified, namely the positive effects of tension and stimulation. These results are consistent with past literature on physical spaces and are compatible with each other. Regarding the increased tension and stimulation effects, physio-psychological explanations such as the suppression of melatonin release can also be given. The findings are thus conclusive from an endocrinological perspective as well.

Comparing daylight and room lighting yielded significant and consistent results for seven visual and non-visual effects. Daylight conclusively led to higher ratings for “beauty,” “liking” and “clarity” and “spaciousness.” For humans, daylight has positive connotations and is also perceived as positive in virtual environments. The daily availability and expectable design of daylight can explain the rating for ordinary versus special. Room lighting can deviate in the way accordingly strongly and makes special possible, thus a lighting scenario outside of the daily experience or expectation. Thus, this result is also plausible. The evaluation of higher brightness goes along with the evaluation of higher stimulation, which is also consistent with past research.

Regarding CCT as an independent variable, the parameters “glare” and “brightness” were evaluated differently in the two studies. This variation may have been due to the device used, the ambient brightness, or other factors. However, a definite cause cannot be determined based on the present data.

For the non-visual ratings, only one parameter, the rating of public and private, deviated from Study VL1 to Study VL2. In the international study, cold light was associated with privacy, whereas in the homogeneous group of German students, warm light was associated with privacy. Similarly, there was a switch in the ratings for daylight and room lighting: in the international group, daylight was rated as offering higher privacy, whereas in the second study, room lighting was rated as more private.

These factors could be related to cultural differences that have already been noted in other studies (H. Lee & Lee, 2021; N.-K. Park et al., 2010; N.-K. Park & Farr, 2007; Quellman & Boyce, 2002). For example, in the Eastern cultural area, which is where 69.5% (India 34,7%, Malaysia 27.4%; South Korea 2.1%, Nepal 2.1%, Pakistan 2.1%, Vietnam 1.1%) of the subjects in the first study originated, cold white lighting is more common in everyday life and in living spaces than in Western Europe (E. Lee & Park, 2011). Thus, different attributions of CCT values to private or public domains, as follows even from the conceptual lighting approach, are quite conclusive. In addition, such a consideration can also be applied to the condition daylight, since daylight has high CCT values and thus corresponds more to cool white lighting. In western culture, warm white lighting is common in private rooms and cold white daylight therefore tends to be associated with the public and activities outside the home. However, more in-depth cultural studies would be necessary to make valid statements about this. These selective differences in single items thus provide interesting starting points for further investigations. The broad confirmation of the effects occurring independently in both studies, meanwhile, indicates the reliable sampling of the visual and non-visual effects of lighting in virtual spaces.

Using ANOVA to identify effects with the same orientation on the measured data of Studies VL1 and VL2 would only be partially appropriate. For instance, while the absolute level of the given ratings differs between Study VL1 and VL2, the statement of the respective study, such as daylight being rated as more spacious than room lighting, is consistent. Consequently, applying ANOVA would indicate a significant difference between the data sets of the two studies. However, this difference would be biased by the differences in absolute rating levels, rendering the ANOVA approach inadequate.

As a further research approach, it could be valuable to combine various conditions in different contexts of the depicted spaces. For instance, we could differentiate virtual spaces designed for private entertainment, business, or education purposes. This approach would enable to explore numerous experimental designs, which could broaden the scope of such studies and provide additional insights.

14.6 Conclusion

Both the biotic and controlled laboratory studies provide essentially the same findings. The measurement tools used appear to be valid and transferable from light research in physical space to virtual space. However, some points require more in-depth research to comprehend deviations and attribute them to interpersonal or technologically induced interference factors. Eleven of 17 effects that were significant in both studies were confirmed to have the same orientation. Virtual daylight instead of room lighting increased evaluations of beauty, likeability, clarity, spaciousness, brightness, stimulation, and ordinariness. High CCT lighting instead of low lighting increased the rating of visual coolness, spaciousness, tension, and stimulation.

15. HCVL as derived approach

15.1 Modeling

Scientific modeling is a common tool used in various fields of science to understand, explain, and predict complex phenomena. By creating simplified representations of real systems, the behavior of these systems can be explored under better conditions and predictions can be made about relationships. In principle, models can be used to test hypotheses, gain new insights, and derive decisions (Grimm et al., 2014). The process of scientific modeling typically involves identifying the key variables and interactions that determine a system's behavior and then constructing a mathematical or computational model that represents those dynamics. The model can then be retested against data or other observations to assess its accuracy and refine its predictions (Augusiak et al., 2014).

Based on experimental Studies VL1, VL2 and the comparison between both VL3, a first HCVL approach and two partial models are created. This is a simplified approach that can evolve into a scientific model in the future through further experimental and empirical data as well as prediction testing.

For model building, the results of the Flynn instrument from both surveys (VL1 and VL2) were integrated and cross-checked. Only if significant results were found at a level of $p < 0.05$ for the respective item in both studies were the results included in the model. If a significant result was found in only one study and thus could not be confirmed by the other study, it was not included in the current approach. However, it is conceivable that the approach and partial models could be expanded to include these aspects if further study results become available from other studies or if interfering variables are identified. The results of the conducted studies provide information about the influence of CCT and daylight in virtual space. In addition, the findings of the preference survey of Study VL2 are included.

15.2 HCVL approach

The results of Study VL1, VL2 and VL3 provide information about the influence of CCT and virtual daylight and report preferences for lighting conditions in virtual environments. Both the study in the biotic environment (VL1) and the study under laboratory conditions (VL2) showed that there are differences in the visual and non-visual evaluation of virtual lighting scenarios. These can be used for the initial design of an approach for lighting in virtual spaces. Complementing the approach of HCL, it can be termed human-centric virtual lighting (HCVL).

First, a general HCVL approach is derived, which is then considered in detail by using the concrete study results already available in two partial models. Thus, on the one hand a partial HCVL model of CCT conditions and on the other hand a partial HCVL model of virtual daylight are derived.

15.2.1 General approach

The results of the virtual lighting exploration are consistent with the findings from previous investigations of physical spaces. Cold white lighting with high CCT levels is considered stimulating and tense and engenders a feeling of greater spaciousness. The integration of virtual daylight is perceived as more beautiful and likeable and increases perceived spaciousness. In addition, the perceived brightness is rated as higher and more stimulating. In comparison to the several types of room lighting, daylight is rated as more ordinary. These findings coincide with the findings from studies of physical spaces. However, the assessment of private to public cannot be included in the approach due to inconsistencies between VL1 and VL2. An explanation for this could be the different cultural backgrounds of the subjects and requires further investigation. The evaluation of brightness at different CCT levels in VL1 and VL2 is also not consistent. Besides cultural differences, this variation could also reflect the influence of the different display devices with heterogeneous technical characteristics.

Based on the studies, it is feasible to state that the color temperature of virtual lighting influences visual and non-visual evaluation via the following semantic differentials:

(1) visually warm – visually cold

(2) confined – spacious

(3) relaxing – tense

(4) stimulating – subduing

Likewise, on the basis of the studies it is thus feasible to state for the influence of virtual daylight on visual and non-visual evaluation in the following semantic differentials:

(1) beautiful – ugly

(2) dislike – like

(3) hazy – clear

(4) confined – spacious

(5) bright – dim

(6) ordinary – special

According to Lakens (2013) effect sizes are the most important outcome of empirical studies. To quantify the effects, the effect sizes from the paired *t*-test and the Wilcoxon-signed-rank test need to be comparable. For this purpose, the findings of *t*-tests from VL1 and VL2 that meet the significance level of $\alpha = .05$, are post-processed to convert Cohen's *d* to Pearson´s *r* as effect size measure (Cohen, 1988; Lenhard & Lenhard, 2017), see Tables 20 and 21.

Table 20

Conversion of effect size measures of consistent findings in VL1 and VL2 regarding CCT levels

Item	VL1		VL2	
	d	*r*	*d*	*r*
Visual temperature	0.920	.42	3.227	.85
Spaciousness	1.960	.70	2.017	.71
Relaxation	0.472	.23	2.017	.71
Stimulation	0.347	.17	1.388	.57

Note. N(VL1) = 95; *N(VL2)* = 106.

Table 21

Conversion of effect size measures of consistent findings in VL1 and VL2 regarding daylight conditions

Item	VL1		VL2	
	d	*r*	*d*	*r*
Beauty	0.309	.15	2.577	.79
Likeability	0.435	.21	2.414	.77
Hazy	0.619	.30	0.923	.30
Privacy	0.803	.37	0.973	.44
Spaciousness	0.562	.27	1.960	.70
Brightness	1.931	.69	1.653	.64
Stimulation	0.581	.28	0.477	.23
Specialty	0.918	.42	0.458	.22

Note. N(VL1) = 95; *N(VL2)* = 106.

Using Pearson´s *r* as measure of effect size, the values are consistently scaled between -1 and 1 and are therefore more suitable for comparison and standardization than Cohen's *d*, which has no limitation. According to Rosnow and Rosenthal (2003) elaborated methods to compare effect sizes like Fisher *z*-transformation need much higher samples sizes than given in the previous studies. For example to achieve a power level of .80 in trying to detect a difference of .10 at $p = .05$ (two-tailed) between r_1 and r_2, each sample need a size of n = 1,600 (Rosnow & Rosenthal, 2003).

The classification into small, medium and large effect sizes is according to Cohen (1988). Cohen (1988) interprets $r = .10$ as a small effect, comparable to $d = 0.2$. For $d = 0.5$ Cohen attributes $r = .243$ and a medium effect. For $d = 0.8$ respectively $r = .371$, Cohen refers to a large effect. Therefore, the interpretation and visualization of the partial HCVL models for CCT and daylight conditions are based on the following simplified scheme: $r \geq .10 < .24$ is indicated as small effect (one arrow); $r \geq .24 < .37$ is indicated as medium effect (two arrows); $r \geq .37$ is indicated as large effect (three arrows).

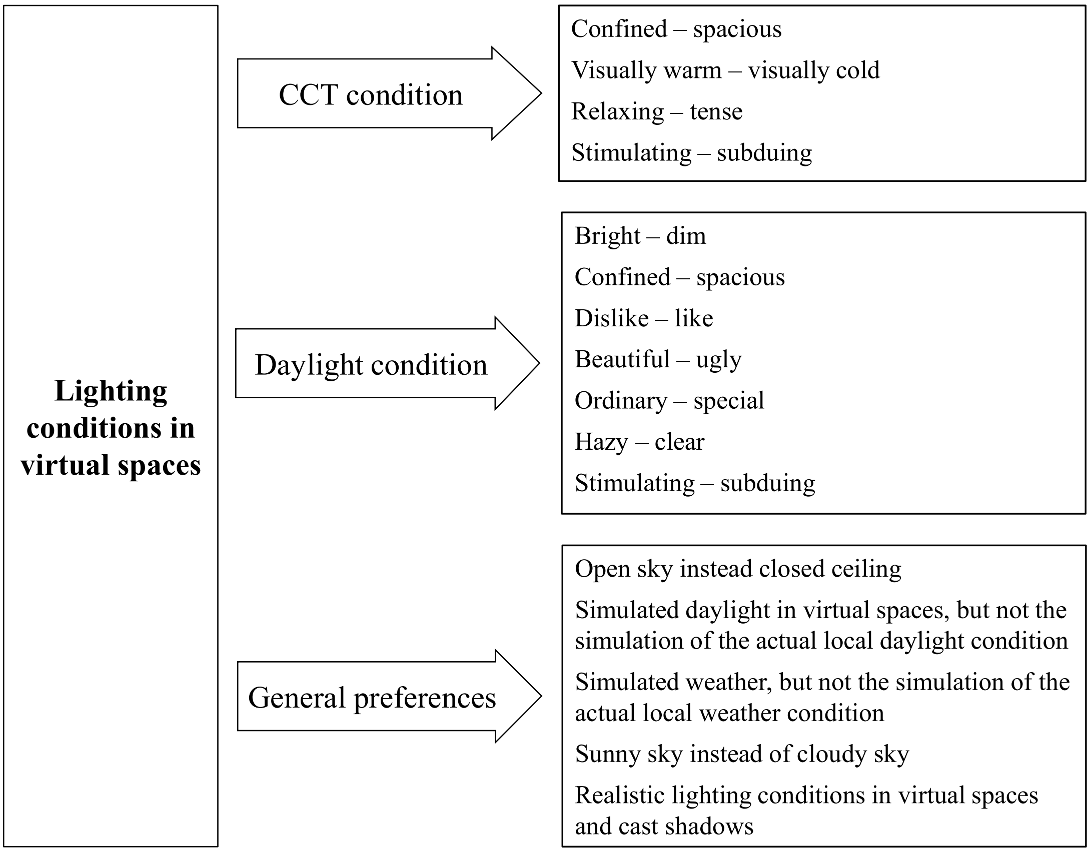
Beyond the findings of the rendering evaluation, results of a preference survey in VL2 clearly showed that people have general preferences for lighting conditions in virtual spaces. The results were measured on a bipolar scale from -3 to +3. Thus, items with an affirmative statement have a mean, median, and mode that are all positive, while negative evaluations have a negative mean, median, and mode. The distribution of responses to preferences in virtual spaces, shown in Study VL2 Section 13.4, provides additional information about the validity of the statement.

Per the results, physically realistic lighting (M = 2.06, Mdn = 2, SD = 1.19) and shadows (M = 1.21, Mdn = 1, SD = 1.42) were preferred. Daylight was strongly preferred (M = 2.21, Mdn = 3, SD = 1.22), as was a sunny sky rather than a cloudy sky (M = 2.10, Mdn = 3, SD = 1.32). In contrast, simulation of local weather conditions (M = -1.26, Mdn = -2, SD = 1.72) and daylight conditions (M = -0.88, Mdn = -1, SD = 1.85) was not attractive.

The draft an HCVL approach shown in Figure 12 includes information about the influence of CCT and daylight as well as generally assumed preferences.

Figure 12

HCVL approach of visual and non-visual effects and preferences



Note. Effects of CCT and daylight conditions derived from VL1 (N = 95) and VL2 (N = 106); general preferences derived from VL2.

15.2.2 Partial HCVL model of CCT conditions

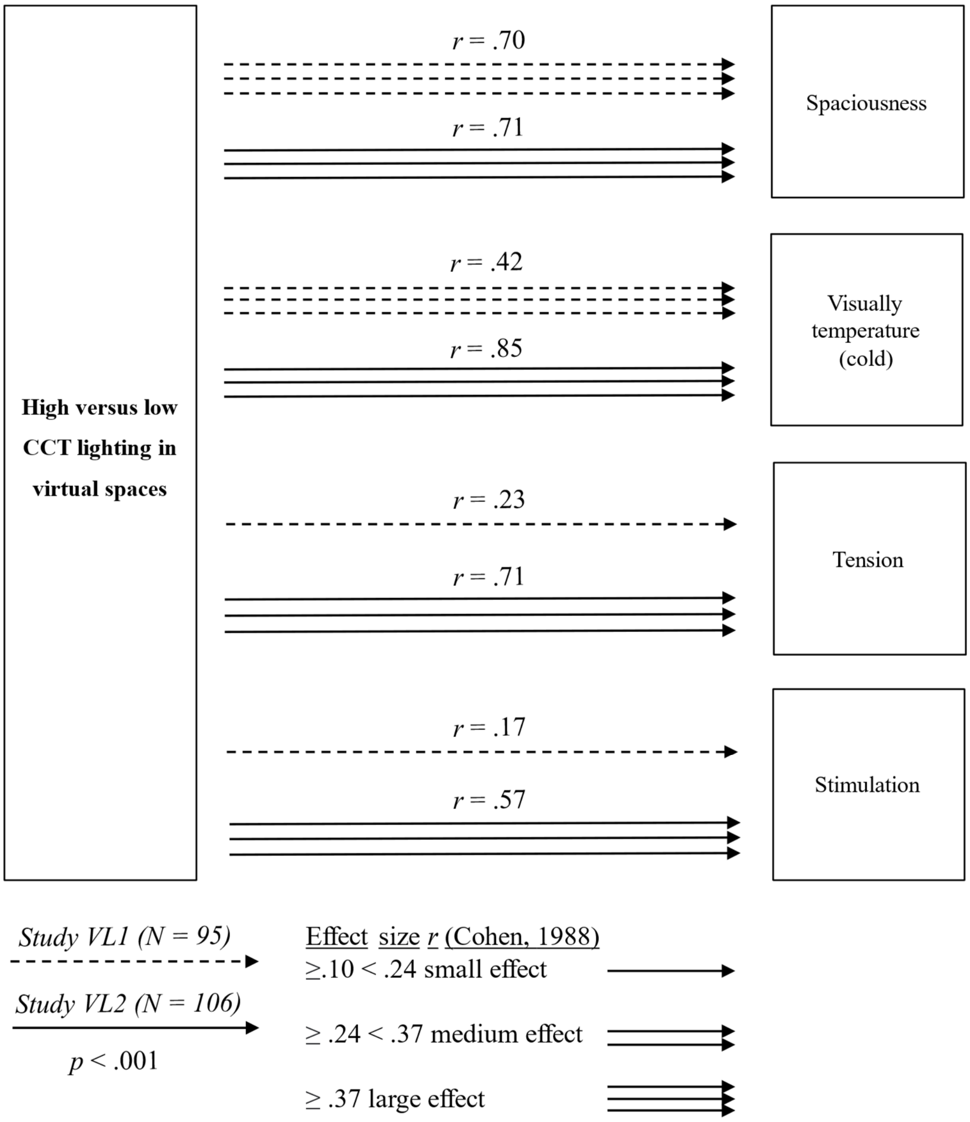
In summary, the following, more detailed model is based on studies of the effects of cold versus warm lighting (see Fig. 13). Taking cold white lighting with high CCT levels (> 5,300 K) as a perspective of the analysis, visual and non-visual effects on four areas can be identified. With large effect sizes in both studies (r = .70, r = .71), the perception of the virtual space was rated as more spacious. With also large effect sizes studies (r = .42, r = .85), cold white virtual lighting was also rated as visually cold. An evaluation of relaxation versus tenseness was measured in VL1 with a small effect size (r = .23), whereas VL2 yielded a large effect size (r = .71). A small effect size (r = 0.17) was identified in VL1 than in VL2 (r = .57) for the stimulating versus subduing differentiation.

This results in the following draft for a partial HCVL model of CCT conditions in virtual spaces (see Fig. 13), which shows the respective effect sizes of the studies and thus allows conclusions to be drawn about expected effects. The effects were ranked according to the strength classification of the respective effects, starting with the largest effects, thus beginning, for example, with "Spaciousness" in CCT, which was found to have a high effect strength in both VL1 (r = .70) and VL2 (r = .71). If no clear ranking resulted from the classification into small, medium, and large, these were sorted by the sum of the effect sizes of VL1 and VL2. This is the case, for example, with "Tension" and "Stimulation" in CCT, both of which had small effect sizes in VL1 (r = .23; r = .17) but large effect sizes in VL2 (r = .71; r = .57). However, "Tension" showed higher values when looking at the concrete effect sizes instead of the classification only, and therefore this is ranked above "Stimulation".

This first draft to a model can be used for predictions of visual and non-visual effects with respect to warm and cold CCT conditions. For example, one prediction of the model may be that virtual spaces are perceived as more spacious when presented in a cold white rather than warm white lighting scenario (r = .70; r = .71). High CCT values of virtual lighting should thus also be associated with a higher evaluation of spaciousness in future trials. Through further studies, such a model can be continuously enhanced, corrected and validated. Indeed, the more elaborate a model is, the more reliably it can be used to derive recommendations for the practical design and use of virtual spaces.

Figure 13

Partial HCVL model of CCT conditions in virtual spaces



15.2.3 Partial HCVL model of virtual daylight

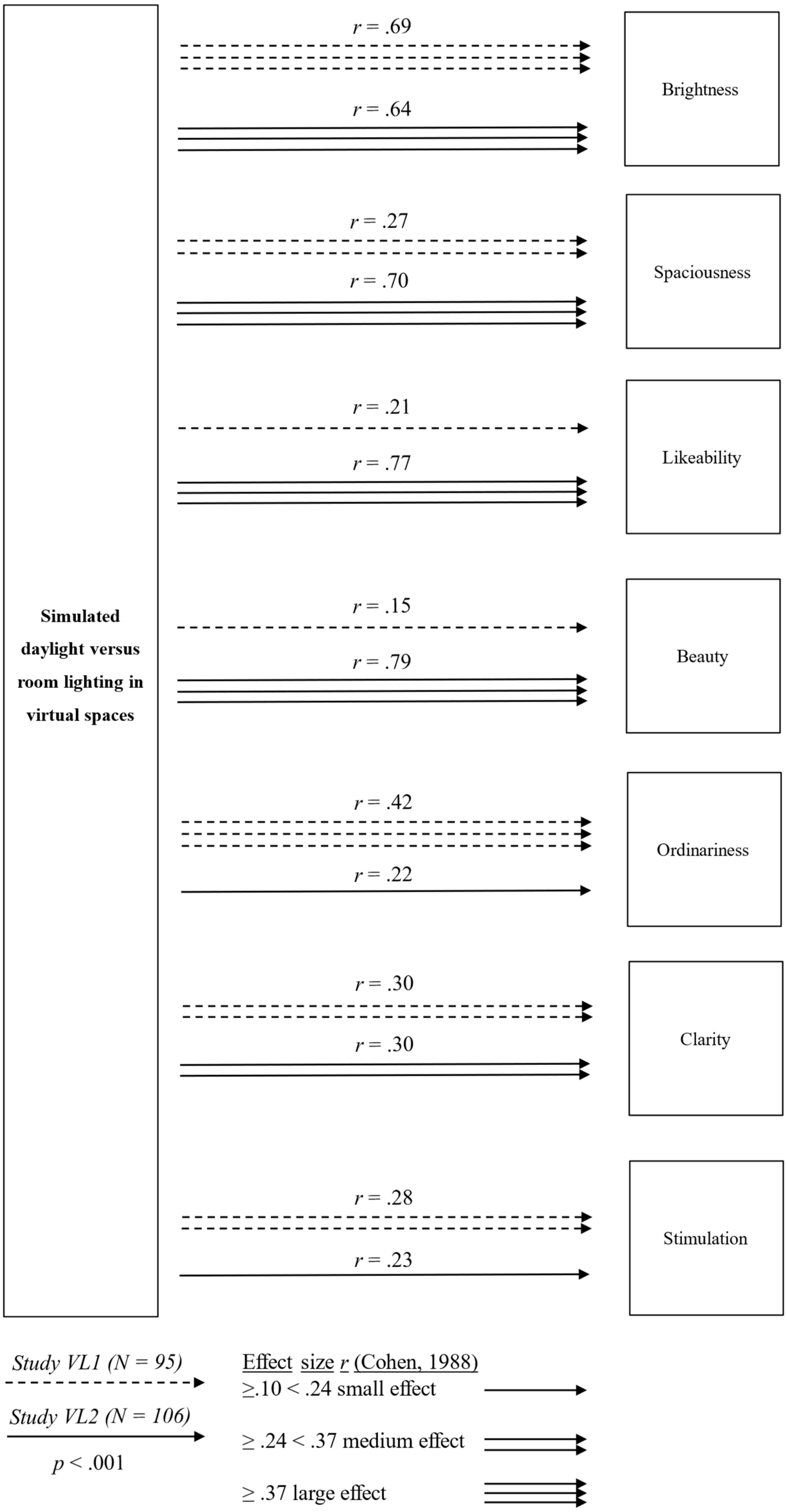
In summary, the following more detailed model is based on the effects of virtual daylight versus room lighting (see Fig. 14). The structure of the model and the procedure of ranking the effects are consistent to the partial HCVL model of CCT conditions in virtual spaces, see Section 15.2.2.

By analyzing daylight, visual and non-visual effects on seven areas can be identified using the previous studies. With a small effect size in VL1 (r = .15) and a large effect size in

VL (*r* = .79), virtual daylight was rated as beautiful rather than ugly. With small and large effect sizes (*r* = .21, *r* = .77), daylit virtual space was evaluated as likeable. Haziness versus clarity was measured in VL1 (*r* = .30) and VL2 (*r* = .30) with a medium effect size. The perception of the virtual space was rated as confined to more spacious with medium effect sizes (*r* = 0.27, *r* = .70). The evaluation of brightness was higher in daylight scenarios than in room lighting scenarios with large effect sizes in both studies (*r* = .69, *r* = .64). Virtual daylight was rated as more stimulating than subduing with medium (*r* = .28) and straight nor small effect (*r* = .23). In VL1 (*r* = .30) and VL2 (*r* = .30), virtual daylight was rated as ordinary rather special with medium effect sizes.

Figure 14

Partial HCVL model of daylight in virtual spaces



15.3 Discussion

The preceding sections presented the initial draft for a new HCVL approach and subsequent partial models. Further information and data are necessary to further develop and validate the models. Based on this approach and models, hypothesis testing, and predictions can be made that can lead to critical further development. Investigation of further correlations and interfering variables is possible.

Despite the potential of modeling, it must be kept in mind that light perception and evaluation are combined psychological, physiological, and physical phenomena.

Pilkey and Pilkey-Jarvis (2007) argue that environmental scientists cultivating a kind of "physics envy" and trying to calculate complex phenomena the way physicists do for atomic behavior. Many disciplines tend to use math-based predictive models that mismatch reality. Therefore, self-critical reflection is appropriate in model development. The HCVL approach does not claim to be a mathematically exact calculation, but rather represents the depiction of probable effects at different virtual illumination parameters.

The basic contents of the models are coherent and plausible based on existing literature. The preferences discussed in Part II of this thesis regarding conceptual lighting can be compared with the preferences presented here. It should be noted that the survey in Study VL2, on which the current preference statements in HCVL are based, asked for general preferences, but specific contexts (e.g., gaming, business, education, etc.) could produce unique, context-dependent evaluations. No conclusive statement can be made about this on the basis of Study VL2, and context must therefore be investigated in further studies.

The model's fields of application and its recommendations for the design of virtual spaces and Metaverse environments are manifold. For example, a stimulating effect can be promoted using high CCT lighting scenarios and virtual daylight and can be useful for creating human-centered lighting in education or business applications. In virtual trainings, for instance, the user should remain as attentive, awake, and concentrated as possible; thus, a stimulating effect through visual stimuli is in the user's interest.

15.4 Conclusion

The HCVL approach presented in this paper serves as an initial framework for developing a scientifically grounded model, which requires further validation and refinement. The approach's partial models for CCT and virtual daylight effects are based on assumptions from two studies, and only results from biotic and controlled laboratory environments, each with a significance level of $p < 0.05$ and consistent findings, have been integrated. In addition, a preference survey was conducted to gather information on users' lighting preferences in virtual spaces. The plausibility of the results was reviewed against current literature. Similar to the HCL approach used in physical spaces, the HCVL approach can be used to optimize visual stimuli and enhance the human-centered experience in virtual spaces.

PART IV: GENERAL DISCUSSION

This part of the thesis reflects on the content of Parts I, II, and III. After a brief summary of the results and HCVL approach, contributions, limitations, and further research are presented. Practical implications are identified for different contexts related to both HCL and HCVL. An overall conclusion completes the thesis.

16. Discussion

16.1 Summary of overall results and HCVL approach

Definite effects of lighting conditions on complex human behavior are difficult to investigate and have only been verified to a limited extent through current studies. The critical examination and experimental investigations of this thesis demonstrated that the constructs and causal relationships discussed in scientific discourse cannot be replicated unambiguously. There are many parameters to consider in studies of lighting effects, whether in physical or virtual spaces. These can be isolated and controlled through laboratory situations, but they lose validity in real-world situations.

Research outside of a laboratory setting enables better recording of people's perceptions, processing, and behaviors but is subject to various confounding variables. Thus, the biotic environment is both an advantage and a disadvantage. The literature reviews and investigations of this thesis highlighted that there are many findings which must be evaluated for their actual impact on people's everyday lives.

Given the growing popularity of virtual applications and Metaverse, it becomes apparent that lighting research should also be considered in these platforms’ design. Current research has numerous gaps, and corresponding practical approaches have not been adequately considered. Human-centered lighting for virtual spaces therefore represents a key interdisciplinary topic for future research.

16.2 Contributions, limitations, and future research

This thesis comprised both an in-depth elaboration of current research on HCL and investigations of the effects of lighting in physical as well as virtual spaces. This thesis utilized current reporting standards, definitions, and technical capabilities to the best of the author's knowledge. Nevertheless, the thesis experiments in physical space, which were mainly planned, carried out, and analyzed from 2017 to 2019, would likely involve different measurement variants and parameters because developments towards uniform standards that can be used in lighting studies began from 2019 onwards. For example, de Kort (2019) published a tutorial for research on human factors in lighting, and Veitch et al. (2019) discussed the quality criteria of applied lighting studies. This resulted in the CIE's issuance of a technical note in 2020 on conducting light studies with ipRGC-influenced responses (CIE, 2020b).

These standards would affect, for example, the wall color of the laboratory environment of Studies CH1 and CH2. At the time, this was conducted in an established perceptual laboratory with black walls to avoid reflections; to ensure comparability with today's studies, this would need to be changed to a solid white wall color. However, these aspects cannot be changed retrospectively and are therefore critically reflected upon and reported here.

Notably, the research on virtual environments represents the technology and state of research in the period from 2020 to 2022. This period, dominated by the COVID-19 pandemic, was characterized by international debate regarding Metaverse applications, technological innovations, and disruptive changes in user behavior towards digital and virtual communication. This research attempted to address these developments by using real contemporary stimuli applied in the business context. Nonetheless, continuous technical progress in software and hardware means that there will be new capabilities and virtual environments in the future that require further research. In any case, the basic methodology remains valid, as other contemporary studies have shown.

The relevance and applicability of lighting research is not limited to physical spaces and can also be applied to virtual spaces. Based on the emerging Metaverse applications, it can be assumed that this will be a relevant field in the future and that HCL can be used and further developed to create human-centric virtual lighting, abbreviated as HCVL. Existing evaluation methods can continue to be used, but further research depends on the technical progress of both software and hardware such as HMDs.

Research on the human-centered effects of lighting can serve billions of people around the world who are exposed to natural and electric lighting in their daily lives. Visual and non-visual effects in virtual environments already affect millions of people who use virtual technologies. This number is expected to grow rapidly in the coming years as technology advances and becomes more affordable and as digitalization spreads beyond industrialized countries. Virtual technologies have the potential to accompany people in all spheres of daily life in the coming decades and should therefore also be accompanied by scientific research.

16.3 Practical implications

16.3.1 General

Non-image forming aspects of lighting are difficult to transfer to complex constructs and behaviors like conflict handling. The influence of lighting as a directly determining variable must therefore always be viewed critically and reflected upon with the appropriate scientific distance. However, according to the current state of research, there is no dispute that lighting has a fundamentally non-visual effect on people that should be considered accordingly when designing lighting conditions (ISO & CIE, 2022; Vetter et al., 2022). The relevant research findings are gathered under the term HCL and have already been converted into related products by industry. However, it is up to each individual, whether in their own private or business environment, to familiarize themselves with these findings and use them for people's benefit. Especially when lighting decisions are made for many people, as is done in public spaces, trade fairs, congress and event environments, decisions should be handled with appropriate preparation and care for the welfare of the event guests. This concerns, for example, bright lighting with high CCT values when participants want to be alert, high-performing, and concentrated on work. On the other hand, dimmed lighting with low-valued CCT is appropriate for a relaxing atmosphere. Decision-makers must always be aware of their high level of responsibility regarding lighting conditions as guests usually have no opportunity to adjust lighting themselves and are therefore at the mercy of the lighting effects.

16.3.2 Education and office workspaces

HCL

HCL is gaining traction in various applications and has been shown to improve performance, ergonomics, and learning outcomes in work and learning environments. Ergonomics is a critical aspect of HCL, and there are established norms and guidelines that need to be followed to ensure that lighting is optimized for human performance and well-being (Boyce et al., 2022; CIE, 2019; DIN, 2021). Conceptual lighting can further support these expectations by tailoring lighting to specific needs.

HCVL

While there are guidelines for the amount of radiation emitted from computer screens, the way content is displayed and its visual and non-visual effects in AR or VR are not regulated. Therefore, the future use of HMDs in work and learning environments must be carefully considered. These displays are already a field of research for new learning environments (Cao et al., 2023) and can lead to more immersive experiences, which in turn require specific considerations for lighting.

A human-centered design for learning and working environments in virtual spaces and Metaverses is a contributing factor to their long-term success. Preliminary findings from the HCVL approach reveal that lighting is a critical factor in virtual environments. For example, virtual daylight can be used to create the impression of larger spaces. With regard to anxieties such as claustrophobia, larger spaces are not only a comfort factor but can considerably increase the quality of stay for many people in virtual environments.

16.3.3 Healthcare spaces

HCL

The aging population and the increasing demand for healthcare services have made the issue of HCL in healthcare and nursing increasingly relevant.

The expectations of conceptual lighting discussed in this thesis need to be considered when designing lighting for healthcare and nursing environments. For example, in nursing homes, it is important to create a comfortable living environment that resembles a home rather than a clinical setting. This can be achieved using warm, congruent lighting to promote a sense of calm and relaxation. In addition to its aesthetic benefits, HCL can also contribute to the psychological well-being of patients. By promoting a sense of calm and comfort, HCL may reduce stress and anxiety in patients, making them more receptive to treatment and facilitating their recovery. Then again, the availability of bright and cold white lighting is necessary to better ensure hygiene.

To achieve the full benefits of HCL in healthcare and nursing environments, it is essential to involve patients, caregivers, and design professionals in the design process; this will help to ensure that lighting is tailored to the specific needs and preferences of patients and caregivers and that it meets the technical and safety requirements of the healthcare setting.

Overall, the integration of human-centered lighting in healthcare and nursing environments can contribute to the physical, emotional, and psychological well-being of patients.

Further research is needed to investigate the impact of HCL on patient outcomes and to develop design guidelines for healthcare and nursing environments that incorporate the principles of HCL.

HCVL

The effect of light in virtual spaces is also relevant to the healthcare sector. The use of HMDs provides new opportunities for conducting training, conferences, and treatments in virtual environments. To ensure the best possible experience for users, it is important that light in virtual spaces is stimulating and conducive to concentration. The findings from research on HCVL can contribute to achieving these objectives. One potential application of virtual spaces and HMDs in the healthcare sector is in dementia treatment. Studies have shown that exposure to blue-enriched light can improve cognitive function and mood in patients with dementia (Riemersma-van der Lek, Rixt F., 2008). By incorporating this type of lighting into virtual reality environments, HMDs can be used to provide patients with an engaging and immersive experience that could potentially improve their cognitive function and quality of life. Another potential application of VR in the healthcare sector is in remote surgeries. Remote surgeries are increasingly being performed using HMDs, which allow surgeons to see and control the surgical instruments in real-time. To ensure that the visual stimuli in these virtual spaces is conducive to concentration and accuracy, it is important to consider the findings from HCVL research. In addition to therapeutic contexts, virtual spaces are also being used for medical training and conferences. By creating realistic and engaging virtual environments, using realistic three-dimensional spaces could improve the learning experience for medical and nursing professionals.

In summary, the professional use of physical lighting and virtual reality in healthcare offers opportunities to improve both quality of life and outcomes for patients and the learning experience for healthcare professionals. By incorporating insights from HCL and HCVL research, it is more feasible to create physical or virtual environments that are aligned with people's needs.

16.3.4 Residential spaces

HCL

Electric lighting is used by billions of people worldwide, making it an essential aspect of residence and daily life. Technological advancements in LED lighting have made it possible to create lighting that is more adaptable and customizable to the needs of individuals. Smart lighting systems can be designed to change color temperature, intensity, and the direction of light to suit different activities and situations. This flexibility in lighting design provides greater control over lighting conditions, which gives the opportunity to integrate the findings of HCL.

However, there are also cultural and technological differences that need to be considered when investigating human-centered lighting in different regions and contexts. Therefore, comparative research is needed to comprehend people's lighting needs and provide lighting solutions that are appropriate for different cultural preferences, climates, and infrastructural and economic conditions.

HCVL

Based on recent market developments and forecasts, it can be assumed that millions of people will spend hours of their free time in virtual spaces in the future. Accordingly, in addition to lighting in the physical private environment, lighting in virtual spaces is also an influencing factor in quality of stay. An HCVL must therefore also consider people's needs for entertainment, gaming, relaxation, and socialization. For example, to create a relaxing virtual atmosphere, the predictions of the HCVL approach can be used, according to which cold white virtual lighting is associated with a stimulating and tense effect and should be changed to warm white lighting to foster a relaxing atmosphere.

16.3.5 Industrial spaces

HCL

The origins of professional lighting research reach back to the time of industrialization and have been an important driver for scientific investigations and technical developments. In particular, work safety, ergonomics, and performance are often in focus and can be aided by an HCL approach. Proper industrial lighting is crucial in large and high halls that lack access to natural light. Moreover, HCL predictors of circadian effects are particularly relevant for shift work. The cluster analysis for preferences of lighting in different contexts suggests that conceptual lighting should consider expectations and preferences for color temperature, depending on the environment. For workplaces, cool white lighting with high CCT values is generally assumed and preferred. Industrial workplaces commonly use lighting with high CCT levels, which is consistent with the assumed expectations and preferences of industrial workers.

HCVL

In recent years, VR has gained significant attention in the industrial sector as it offers a range of benefits in areas such as training, design, and product visualization. In order to achieve a high degree of realism in virtual reality interactions for various movements, studies are conducted to investigate preference and performance considerations in controller design (Beese et al., 2023). In manufacturing, VR is utilized in product design and prototyping, allowing designers and engineers to create and test products in a virtual environment. This reduces the need for physical prototyping and saves time and resources. In the automotive industry, VR is employed in design reviews and visualizing the final product, which helps to identify potential design flaws and make necessary adjustments before production. The construction industry also benefits from VR technology, as it allows architects and engineers to design and visualize building projects in virtual spaces. Through VR, different design options can be assessed, and the environment can be simulated to identify any potential issues before construction begins. This, in turn, improves the quality of sketches and enhances the overall construction process. Moreover, virtual environments can be used for safety and skill training, allowing workers to practice navigating hazardous situations in a safe setting.

In this regard, as determined in the preference query in VL2, physically realistic lighting is also in demand from users and should therefore be implemented whenever possible. Likewise, shadowing and other features can provide a more immersive experience that is closer to the actual situation being simulated. An abstract rendering that does not include the specifics of the lighting in a given situation is thus of limited validity, and therefore the design of virtual lighting is important. By incorporating insights from lighting research, VR solutions in the industrial sector can be optimized to provide users with an immersive and high-quality experience. Additionally, considering the approach of HCVL can enhance the visual quality of virtual environments, making them more realistic and engaging for users. This is especially important in industries such as manufacturing and construction, where accurate visual representations are crucial for effective design and prototyping.

Overall, it is crucial for industrial companies and VR developers to incorporate interdisciplinary scientific knowledge, including lighting research, into the development of VR solutions.

16.3.6 Public and commercial spaces

HCL

The lighting of public and commercial spaces is a major application area as it affects almost everyone in different situations. People have no decision or choice in this regard and are at the mercy of the lighting situation implemented, for example, in a public square, event location, or store. From the perspective of "social lighting", this can even have an influence on urban development and the social coexistence of entire population groups. Accordingly, the HCL approach is particularly relevant here. Influences on complex behavioral changes such as conflict behavior could not be verified in the thesis experiments, but general preferences can also be transferred to the application of lighting in these scenarios. The stimulating effect of cold white lighting affects public places to the point of potentially disturbing circadian rhythms for residents and influencing pedestrian and road traffic.

Based on the findings of the present research, it can be deduced that people also differentiate between private and public spaces in their expectations. Direct influences on complex behaviors such as conflict behavior, which can also occur particularly in public spaces, cannot be scientifically confirmed. However, stimulating effects can be influenced by parameters such as CCT and type of light and can thus indirectly influence behaviors in situations. The finding that (also virtual) daylight and cold white lighting contribute to perceived spaciousness can be concretely applied. As soon as people have to enter a confined physical or virtual space, as is the case with elevators, aircraft cabins, underground parking garages, tunnels, narrow corridors, and so on, real or simulated high CCT daylighting can increase the perceived spaciousness of the actual space. Recognizing that severe claustrophobia affects 3% – 7% of the world's population (Björkman-Burtscher, 2021; Sun et al., 2021) this human-centered lighting approach may reduce anxiety and improve the quality of stay for countless people. Hence, these concrete derivations offer interesting starting points for new experimental and empirical studies that could scientifically monitor and revalidate these outcomes.

HCVL

Virtual environments allow users to engage with products and services in an immersive way. As companies continue to look for new ways to reach and engage customers, virtual spaces offer a compelling solution with numerous benefits. For example, virtual spaces offer companies the ability to create interactive and immersive experiences for their customers, thus providing a personalized and memorable experience. Virtual spaces also offer businesses the opportunity to reach a wider audience. By creating a virtual storefront or Metaverse showroom, businesses can engage customers from around the world without the need for a physical presence; this can be especially beneficial for small businesses or those with limited resources as it allows them to expand their reach without a large investment. By establishing a virtual storefront, businesses can avoid the costs associated with physical retail spaces, such as rent, utilities and maintenance. In addition, virtual spaces can reduce the need for travel and in-person meetings, saving businesses time and money. Virtual environments also make it easier for companies to gain insights into customer preferences and buying habits by tracking user interactions and behavior in a virtual environment. Quality of stay can be determined by the design of virtual spaces, and insights from HCVL can be applied. In the future, this may also give rise to the need for research into the extent to which, for example, the highlighting of products on display in virtual stores corresponds to the conditions in physical environments. The comparison of study results that are already available in physical research (see Section 2.5.5) offers an interesting approach for improving virtual commercial environments. Metaverse platforms offer a wide range of potential use cases, including the possibility of incorporating dramaturgical designs alongside visual and non-visual aspects. Lighting designers use VR technology to plan physical shows, but the possibilities extend beyond this. For instance, virtual concerts and shows can benefit from dramaturgical lightshow elements to enhance the overall experience as well. Notable artists have already taken to specialized Metaverse platforms (e.g., sensoriumgalaxy.com, wavexr.com, and yabal.io), which are equipped with virtual stages for avatar performances. These platforms have demonstrated their ability to attract high-profile performers, indicating the growing interest and potential for virtual shows. However, there is still a lack of practical research on how to effectively integrate lighting dramaturgy into virtual performances, which emphasizes the need for further research in this area.

16.3.7 Virtual spaces and Metaverse

The use of virtual spaces has grown significantly in recent years, with applications ranging from 3D computer games, virtual meeting spaces, Metaverse platforms, and industrial visualization applications.

Virtual spaces offer more flexibility in design than physical spaces, allowing for greater freedom in creating visual stimuli for users. Therefore, it is essential to consider the visual stimuli presented in virtual spaces and to base the design on scientific principles. The design of virtual spaces affects the experiences and physical reactions of millions of people, making it crucial to understand the impact of lighting conditions in these spaces.

Spatial presence, which refers to the sensation of being present in the presented virtual environment (Schubert et al., 2001), is a crucial element in creating an immersive effect in virtual environments. Immersive interactions experienced with avatars can in turn lead to modified behavior in the real world, which is termed “Proteus effect” (Yee & Bailenson, 2007). Further investigation is being carried out on this phenomenon, such as the impact of embodiment in virtual spaces on the walking speed of individuals in the real world once they exit virtual reality, as investigated by Reinhard et al. (2020). Virtual environments should therefore not be considered as detached or parallel worlds, but rather as entities that interact with the physical world.

The studies in this thesis show that virtual lighting can have similar effects in virtual as in physical spaces. For example, the use of cold white lighting and virtual daylight can enhance the feeling of space, thereby counteracting the claustrophobia that can be triggered by opaque VR glasses (Maples-Keller et al., 2017; Rizhan et al., 2021). Daylight and a visible sky are preferred in virtual space designs to create a more spacious and stimulating environment. However, to provide general recommendations beyond this, further research needs to be conducted. The context of the content presented must also be considered when selecting appropriate virtual lighting scenarios. For example, in an action computer game, a sense of confinement and fear may be created intentionally via the lighting atmosphere.

In AR devices, both the physical environment and the display overlays can affect the user's visual experience. However, concrete studies in this area are lacking, and existing studies in physical and virtual spaces are suitable only for identifying the effects of lighting. Decades of research in physical spaces have led to the establishment of various guidelines and standards for lighting design. These guidelines aim to avoid hazards and provide lighting adapted to people following the HCL approach. First negative effects such as eye fatigue are also studied with virtual lighting (Duffy & Chan, 2002). However, comparable concepts for virtual spaces, such as an HCVL approach with corresponding design recommendations, have not yet been developed.

Given that people will likely spend increasing amounts of time in Metaverse platforms and perhaps build virtual houses, subsequent questions will emerge. One interesting field of investigation is which architectural aspects to incorporate into the design of virtual houses. According to available study results, it can be assumed that windows with a view to the virtual outside world will also be installed in virtual houses, even if they are not technically necessary. Another relevant topic to consider is the availability of light sources in virtual buildings and whether a digital market will emerge for them, as has already been the case for virtual building sites, clothing, and accessories.

16.4 Conclusion

The studies conducted show that people have preferences for lighting in certain contexts such as recreational or performance situations, referred to as conceptual lighting. Both visual effects such as the different evaluation of warm and cold lighting on perceived color temperature, room size, and glare perception as well as non-visual effects such as stimulating effects can be understood through various theoretical reappraisals and original experiments. However, complex constructs like conflict behavior seem to be a stable construct that cannot be determined by the tested lighting conditions as an environmental factor.

This finding affirms that the effects of lighting conditions on human behavior are complex and challenging to investigate. As such, experimental studies are limited in their ability to replicate the constructs and causal relationships discussed in scientific discourse. Studies suggesting associations with complex perceptual, cognitive, or behavioral processes should therefore be viewed critically. Simplified causal relationships according to which light can compel immediate behavior apart from physical responses such as an endocrinological effect through melatonin suppression should be examined. The study of these research areas is complex and characterized by diverse confounding variables.

Lighting effect studies, both in physical and virtual spaces, must consider many parameters, but these can lead to a loss of validity in the real world. Research outside the laboratory allows for better measurements of perceptions, processing, and behaviors, but it is also subject to confounding variables. Literature reviews and research have produced many findings, but these should be critically reflected upon for their implications on everyday life.

As virtual applications and Metaverse grow in popularity, lighting research and its findings should also be considered in the design of such platforms. The current state of research is still incomplete, and relevant approaches have not yet been sufficiently applied to practice. The results of a preference survey provide information about general preferences for lighting in virtual spaces. The initial concept for an HCVL approach can be used to optimize visual stimuli in virtual spaces, support a human-centered user experience, and initiate further research in this new interdisciplinary domain.

On the one hand, the original studies presented here have demonstrated that established measurement methods from physical illumination and perception research can also be applied in virtual environments. On the other hand, this thesis has illustrated that more importance needs to be given to lighting simulation in virtual spaces. Looking at current popular virtual environments, no adequate and scientifically based lighting concepts are in use. The available literature provides ample guidance on human-centered lighting in work, home and public contexts, but these are limited to physical environments.

Thus, more research is needed, and technology providers, public and corporate investors, virtual event organizers, and users of virtual environments need to be made aware of the importance of the visual and non-visual effects of lighting. Overall, this work emphasizes the relevance of research involving various disciplines such as architecture, business management, computer science, design, engineering, ergonomics, lighting research, medicine, physics, psychology, and other relevant fields to advance knowledge about the effects of lighting.

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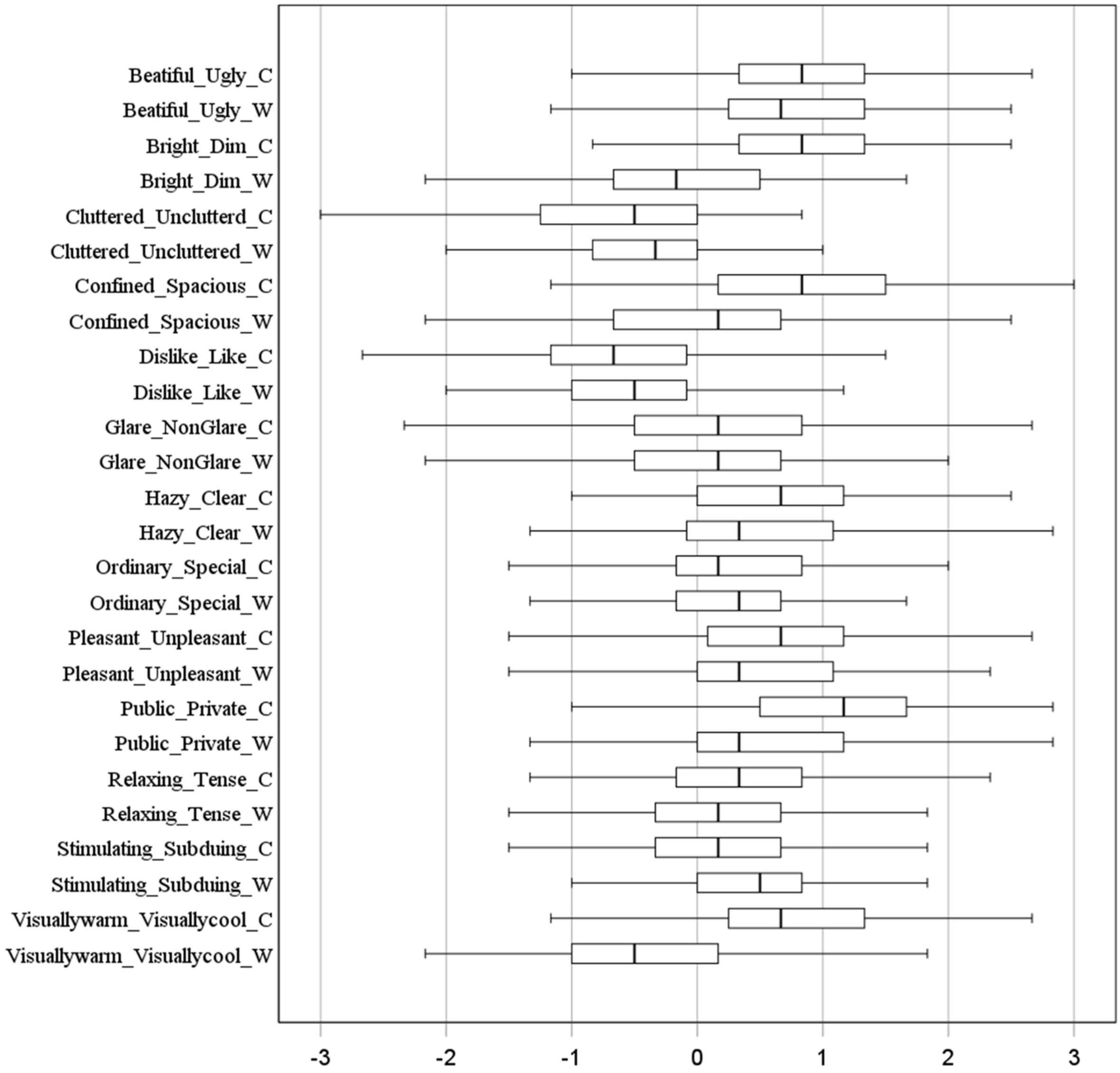
Appendix

Supplemental Figures

Figure A1

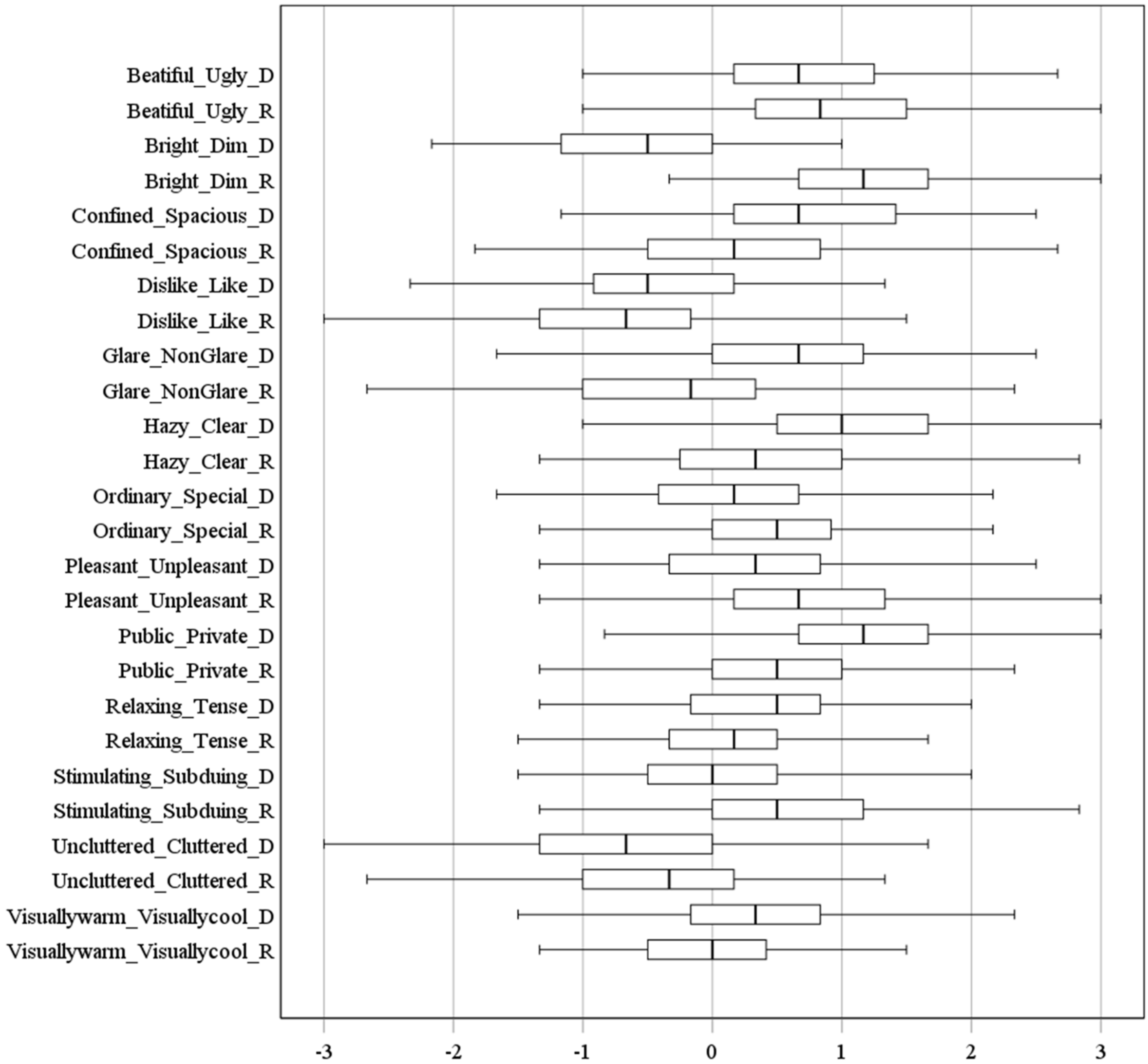
Boxplot of Flynn´s semantic differential rating scales for warm / cold lighting condition VL1



Note. N = 95; C = cold lighting condition; W = warm lighting condition.

Figure A2

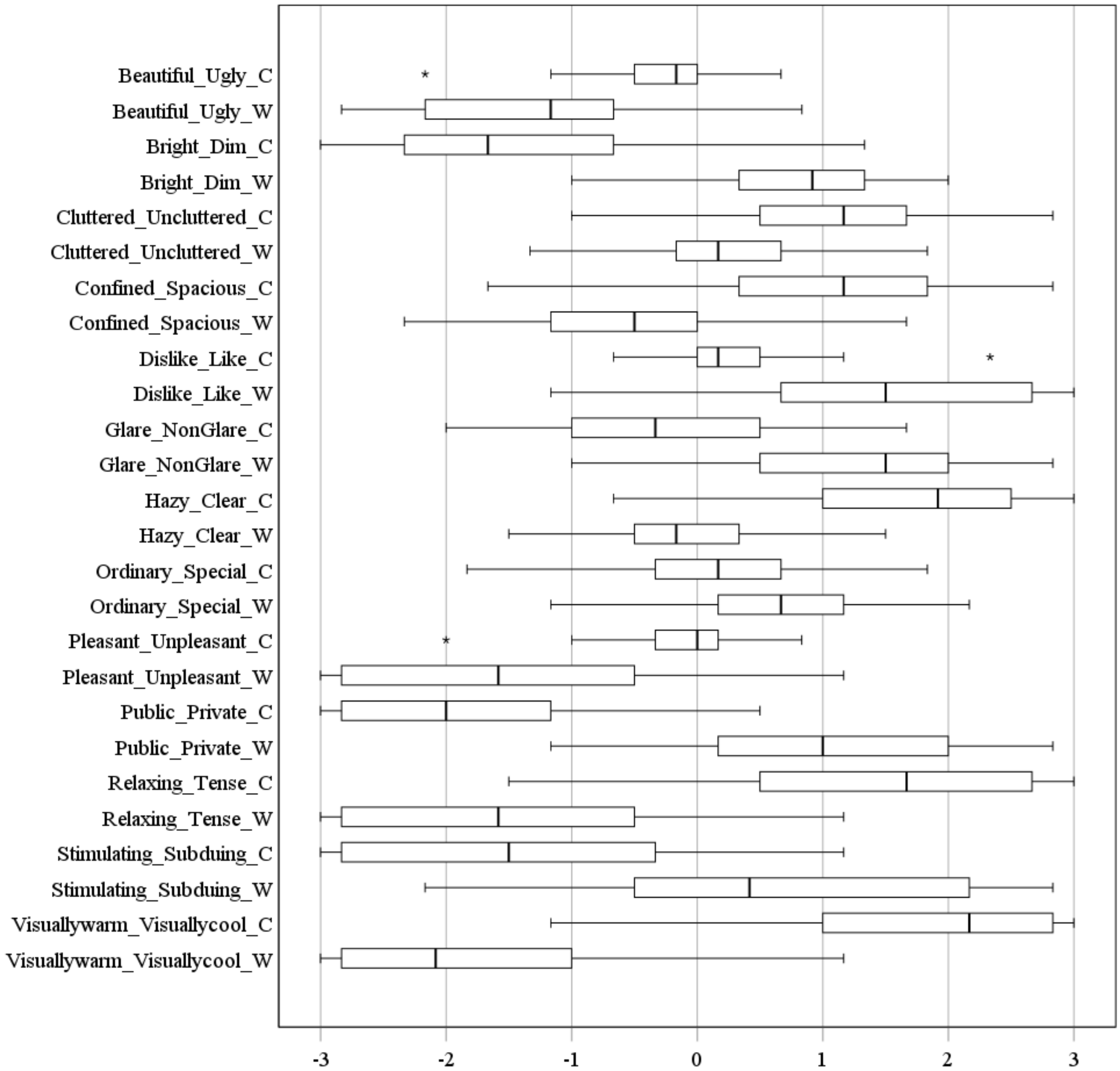
Boxplot of Flynn´s semantic differential rating scales for room lighting / daylight condition VL1



Note. N = 95; D = daylight condition; R = room lighting condition.

Figure A3

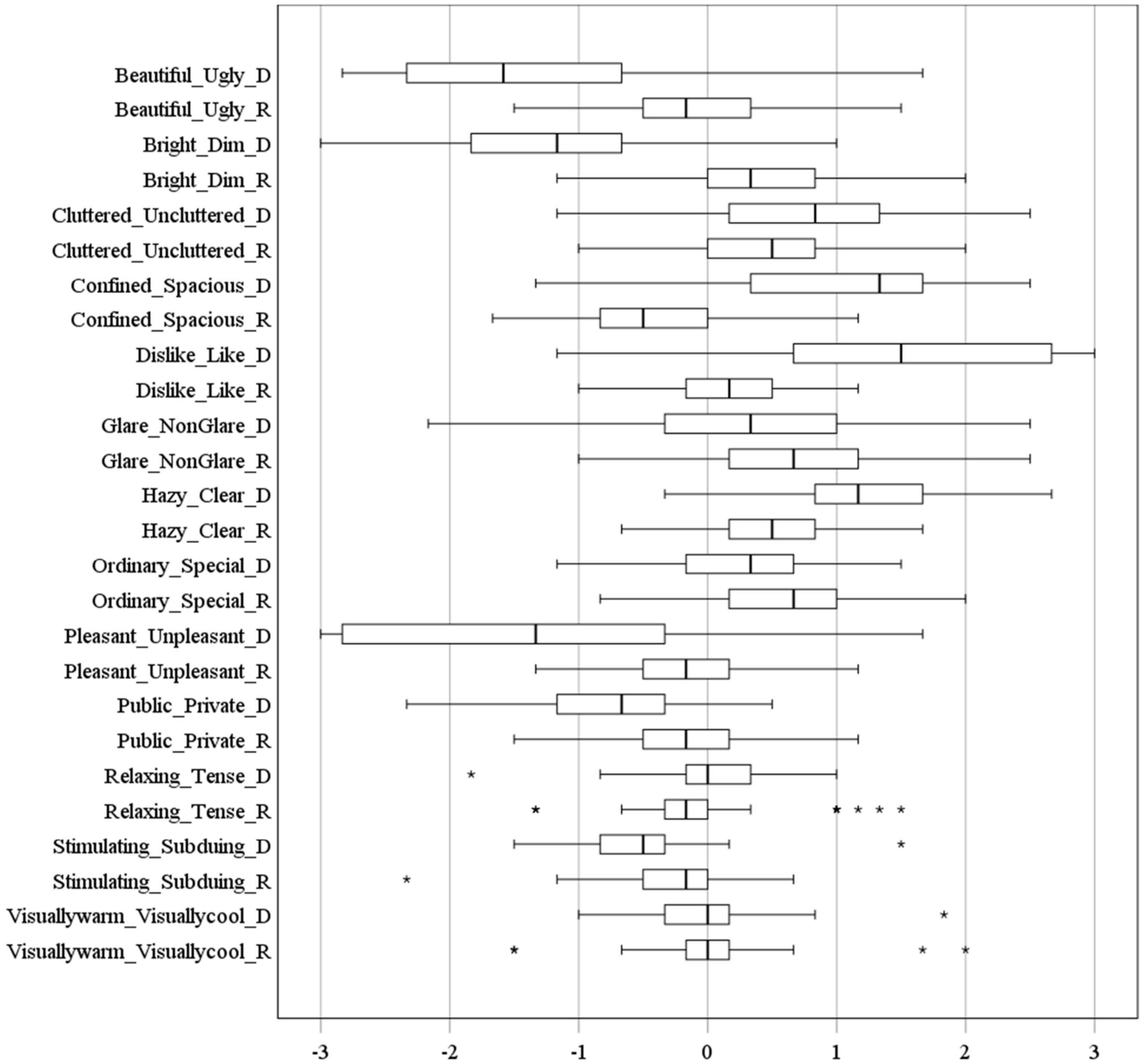
Boxplot of Flynn´s semantic differential rating scales for warm / cold lighting condition VL2



Note. N = 106; C = cold lighting condition; W = warm lighting condition; *Outliers that are more than three times the interquartile range (IQR) away from the nearest quartile.

Figure A4

Boxplot of Flynn´s semantic differential rating scales for room / daylight lighting condition VL2



Note. *N* = 106; D = daylight condition; R = room lighting condition; *Outliers that are more than three times the IQR away from the nearest quartile.

Supplemental Tables

Table A1

Tests of between-subject effects for competing CH1

Source	*SS*	*df*	*MS*	*F*	*p*
LightingCondition	12.360	1	12.360	1.189	.278
Case	1.654	1	1.654	0.159	.691
LightingCondition × Case	12.360	1	12.360	1.189	.278
Block	10.066	1	10.066	0.968	.327
LightingCondition × Block	23.890	1	23.890	2.298	.132
Case × Block	10.066	1	10.066	0.968	.327
LightingCondition × Case × Block	3.243	1	3.243	0.312	.577

Note. $N = 68$.

Table A2

Lighting condition main effect for competing CH1

Lighting condition	*M*	*SE*	*95% CI*	
			LL	*UL*
Warm	5.162	0.391	4.388	5.935
Cold	4.559	0.391	3.785	5.332

Note. $N = 68$.

Table A3

Tests of between-subjects effects for collaborating CH1

Source	*SS*	*df*	*MS*	*F*	*p*
LightingCondition	0.184	1	0.184	0.048	.827
Case	0.184	1	0.184	0.048	.827
LightingCondition × Case	11.184	1	11.184	2.906	.091
Block	14.890	1	14.890	3.869	.051
LightingCondition × Block	0.360	1	0.360	0.094	.760
Case × Block	0.360	1	0.360	0.094	.760
LightingCondition × Case × Block	0.007	1	0.007	0.002	.965

Note. $N = 68$.

Table A4

Tests of between-subjects effects for compromising CH1

Source	*SS*	*df*	*MS*	*F*	*p*
LightingCondition	1.243	1	1.243	0.331	.566
Case	1.243	1	1.243	0.331	.566
LightingCondition × Case	6.184	1	6.184	1.649	.201
Block	35.007	1	35.007	9.333	.003**
LightingCondition × Block	0.890	1	0.890	0.237	.627
Case × Block	0.890	1	0.890	0.237	.627
LightingCondition × Case × Block	1.243	1	1.243	0.331	.566

Note. ** $p < .01$.

Table A5

Lighting condition and case interaction effect for avoiding CH1

Lighting condition	Case	*M*	*SE*	*95% CI*	
				LL	*UL*
Warm	Student	7.088	0.323	6.448	7.728
	Landlord	5.912	0.323	5.272	6.552
Cold	Student	6.412	0.323	5.772	7.052
	Landlord	7.324	0.323	6.684	7.964

Note. $N = 68$.

Table A6

Block main effect for accommodating CH1

Block	*M*	*SE*	*95% CI*	
			LL	*UL*
1	5.794	0.317	5.167	6.421
2	3.765	0.317	3.138	4.392

Note. $N = 68$.

Table A7

Lighting condition and interaction effect for accommodating CH1

Lighting condition	Block	*M*	*SE*	*95% CI*	
				LL	*UL*
Warm	1	6.029	0.448	5.143	6.916
	2	3.000	0.448	2.113	3.887
Cold	1	5.559	0.448	4.672	6.446
	2	4.529	0.448	3.643	5.416

Note. N = 68.

Table A8

Paired samples statistics emotional states CH2

	Lighting condition	*M*	*SD*	*SE*
Motivation	warm	0.22	1.09	0.132
	cold	0.323	1.01	0.122
Creativity	warm	0.43	0.96	0.117
	cold	0.382	0.96	0.116
Comfort	warm	0.31	1.22	0.149
	cold	0.161	1.27	0.153
Happiness	warm	0.19	1.20	0.146
	cold	0.102	1.25	0.153
Anxiousness	warm	0.24	1.13	0.138
	cold	0.176	1.10	0.136

Note. N = 68.

Table A9

Paired samples test emotional states CH2

	Paired Differences							
			SE	*95% CI*				
	M	*SD*	*Mean*	*LL*	*UL*	*t*	*df*	*p*
Motivation	-.102	1.29	0.156	-0.416	0.210	-0.656	67	.514
Creativity	0.0441	0.99	0.121	-0.197	0.285	0.364	67	.717
Comfort	0.147	1.51	0.182	-0.218	0.512	0.804	67	.424
Happiness	0.0882	1.43	0.173	-0.258	0.434	0.508	67	.613
Anxiousness	0.0588	1.08	0.130	-0.201	0.319	0.450	67	.654

Note. N = 68.

Table A10

Paired samples statistics SAM CH2

	Lighting condition	*M*	*SD*	*SE*
SAM Dominance	reddish	56.26	21.23	2.574
	bluish	59.28	17.69	2.145
SAM Arousal	reddish	65.24	21.45	2.601
	bluish	70.40	20.61	2.500
SAM Pleasure	reddish	37.26	18.14	2.200
	bluish	31.99	15.95	1.934

Note. $N = 68$.

Table A11

Paired samples SAM CH2

	Paired Differences							
				95% CI				
	M	*SD*	*SE*	*LL*	*UL*	*t*	*df*	*p*
Dominance	-3.015	19.25	2.334	-7.673	1.644	-1.292	67	.201
Arousal	-5.162	23.25	2.819	-10.789	.466	-1.831	67	.072
Pleasure	5.279	19.48	2.363	.563	9.995	2.234	67	.029*

Note. $N = 68$; * $p < .05$, ** $p < .01$.

Table A12

Results structural equation modelling SAM with lighting condition and block CH2

SAM	Variable	*Coefficient*	*SE*	*z*	*p*	*-95% CI*	*+95% CI*
SAM Dominance	Block	0.062	0.085	0.73	0.464	-0.104	0.229
	Lighting Condition	0.077	0.085	0.91	0.362	-0.089	0.244
	_cons	2.830	0.239	11.85	0.000	2.362	3.298
SAM Arousal	Block	0.016	0.085	0.19	0.847	-0.150	0.183
	Lighting Condition	0.123	0.084	1.46	0.145	-0.042	0.288
	_cons	3.084	0.251	12.3	0.000	2.593	3.576
SAM Pleasure	Block	0.005	0.085	0.06	0.956	-0.161	0.171
	Lighting Condition	-0.154	0.083	-1.85	0.065	-0.317	0.009
	_cons	2.167	0.185	11.73	0.000	1.805	2.529
Correlation	Dominance x Arousal	0.369	0.074	4.99	0.000	0.224	0.515
	Dominance x Pleasure	0.079	-3.620	-3.62	0.000	-0.439	-0.131
	Arousal x Pleasure	-0.349	0.075	-4.63	0.000	-0.496	-0.201

Note. $N = 68$.

Table A13

Paired samples statistics emotional states CH2

Item	Lighting condition	*M*	*SD*	*SE*
Motivation	reddish	0.40	0.92	0.111
	bluish	0.62	0.99	0.120
Creativity	reddish	0.26	0.92	0.112
	bluish	0.35	0.89	0.108
Comfort	reddish	0.43	1.11	0.135
	bluish	0.59	1.07	0.130
Happiness	reddish	0.24	0.99	0.121
	bluish	0.49	0.95	0.116
Anxiousness	reddish	0.57	0.98	0.119
	bluish	0.60	0.93	0.113

Note. $N = 68$.

Table A14

Paired samples test emotional states CH2

Item	Paired Differences							
				95% CI				
	M	*SD*	*SE*	*LL*	*UL*	*t*	*df*	*p*
Motivation	-0.221	1.05	0.127	-0.474	0.033	-1.734	67	.087
Creativity	-0.088	1.06	0.129	-0.345	0.169	-0.686	67	.495
Comfort	-0.162	1.21	0.146	-0.453	0.130	-1.107	67	.272
Happiness	-0.250	1.11	0.135	-0.519	0.019	-1.855	67	.068
Anxiousness	-0.029	1.04	0.126	-0.280	0.221	-0.234	67	.816

Note. $N = 68$.

Table A15

Block and case interaction effect for competing CH2

Block	Case	*M*	*SE*	*95% CI*	
				LL	*UL*
1	Student	6.000	0.543	4.926	7.074
	Landlord	4.647	0.543	3.573	5.721
2	Student	5.294	0.543	4.220	6.368
	Landlord	7.794	0.543	6.720	8.868

Note. $N = 68$.

Table A16

Case main effect difference for collaborating CH2

Case	*M*	*SE*	*95% CI*	
			LL	*UL*
Student	6.118	0.226	5.670	6.566
Landlord	5.456	0.226	5.008	5.904

Note. N = 68

Table A17

Block and case interaction effect for collaborating CH2

Block	Case	*M*	*SE*	*95% CI*	
				LL	*UL*
1	Student	6.353	0.320	5.719	6.987
	Landlord	4.588	0.320	3.955	5.222
2	Student	5.882	0.320	5.249	6.516
	Landlord	6.324	0.320	5.690	6.957

Note. N = 68

Table A18

Tests of between-subjects factors for compromising CH2

Source	*SS*	*df*	*MS*	*F*	*p*
LightingCondition	3.243	1	3.243	0.741	.391
Case	7.066	1	7.066	1.614	.206
LightingCondition × Case	2.125	1	2.125	0.486	.487
Block	2.125	1	2.125	0.486	.487
LightingCondition × Block	7.066	1	7.066	1.614	.206
Case × Block	1.243	1	1.243	0.284	.595
LightingCondition × Case × Block	1.243	1	1.243	0.284	.595

Note. N = 68.

Table A19

Interaction effect lighting condition and block for avoiding CH2

Lighting condition	Block	*M*	*SE*	*95% CI*	
				LL	*UL*
Reddish	1	6.912	0.338	6.242	7.581
	2	6.529	0.338	5.860	7.199
Bluish	1	7.235	0.338	6.566	7.905
	2	6.265	0.338	5.595	6.934

Note. $N = 68$.

Table A20

Block main effect difference for avoiding CH2

Block	*M*	*SE*	*95% CI*	
			LL	*UL*
1	7.074	0.239	6.600	7.547
2	6.397	0.239	5.924	6.870

Note. $N = 68$.

Table A21

Block main effect for accommodating CH2

Block	*M*	*SE*	*95% CI*	
			LL	*UL*
1	4.882	0.323	4.244	5.521
2	3.971	0.323	3.332	4.609

Note. $N = 68$.

Table A22

Interaction effect lighting condition and block for accommodating CH2

Lighting Condition	Block	*M*	*SE*	*95% CI*	
				LL	*UL*
Reddish	1	4.147	0.457	3.244	5.050
	2	4.647	0.457	3.744	5.550
Bluish	1	5.618	0.457	4.714	6.521
	2	3.294	0.457	2.391	4.198

Note. $N = 68$.

Table A23

Interaction effect case and block for accommodating CH2

Block	Case	*M*	*SE*	*95% CI*	
				LL	*UL*
1	Student	3.735	0.457	2.832	4.639
	Landlord	6.029	0.457	5.126	6.933
2	Student	5.382	0.457	4.479	6.286
	Landlord	2.559	0.457	1.655	3.462

Note. $N = 68$.

Table A24

ANOVA contrasts lighting preferences CH2

Test			*Contrast*	*SE*	*t*	*p*	*-95% CI*	*+95% CI*
10	vs	1	-1808.00	378.614	-4.78	.000	-3102.78	-513.22
11	vs	1	-1362.26	378.614	-3.60	0.026	-2657.04	-67.47
13	vs	1	-1419.17	378.614	-3.75	0.014	-2713.95	-124.39
10	vs	2	-2088.56	378.614	-5.52	0.000	-3383.34	-793.77
11	vs	2	-1642.82	378.614	-4.34	0.001	-2937.60	-348.03
12	vs	2	-1338.24	378.614	-3.53	0.033	-2633.02	-43.45
13	vs	2	-1699.73	378.614	-4.49	0.001	-2994.51	-404.94
10	vs	3	-2107.90	378.614	-5.57	0.000	-3402.69	-813.12
11	vs	3	-1662.16	378.614	-4.39	0.001	-2956.95	-367.38
12	vs	3	-1357.58	378.614	-3.59	0.027	-2652.37	-62.80
13	vs	3	-1719.07	378.614	-4.54	0.000	-3013.86	-424.29
10	vs	5	-2147.15	378.614	-5.67	0.000	-3441.93	-852.36
11	vs	5	-1701.40	378.614	-4.49	0.001	-2996.19	-406.62
12	vs	5	-1396.82	378.614	-3.69	0.018	-2691.61	-102.04
13	vs	5	-1758.32	378.614	-4.64	0.000	-3053.10	-463.53
10	vs	6	-1223.85	378.614	-3.23	0.098	-2518.63	70.94
10	vs	7	-2240.28	378.614	-5.92	0.000	-3535.06	-945.50
11	vs	7	-1794.54	378.614	-4.74	0.000	-3089.32	-499.75
12	vs	7	-1489.96	378.614	-3.94	0.007	-2784.74	-195.17
13	vs	7	-1851.45	378.614	-4.89	0.000	-3146.23	-556.66
10	vs	8	-2193.46	378.614	-5.79	0.000	-3488.24	-898.67
11	vs	8	-1747.71	378.614	-4.62	0.000	-3042.50	-452.93
12	vs	8	-1443.13	378.614	-3.81	0.011	-2737.92	-148.35
13	vs	8	-1804.63	378.614	-4.77	0.000	-3099.41	-509.84

$F(12,1755) = 8.81$, $p < .001$, adj. $R^2 = 0.050$

Note. $N = 68$.

Table A25

Cluster analysis lighting preferences CH2

Test	Cluster 1	Cluster 2	Cluster 3	Cluster 4	ANOVA	*adj.* R^2	2 vs. 1	3 vs. 1	4 vs. 1	3 vs. 2	4 vs. 4	4 vs. 3
CIEtest1	4935.68	7910.72	8586.45	10713.89	$F(3,132) = 26.84$*	0.365	< .001	< .001	< .001	1.000	< .05	< .10
CIEtest2	5535.31	7422.41	10302.70	10019.28	$F(3,132) = 31.13$*	0.401	< .01	< .001	< .001	< .001	< .01	1.000
CIEtest3	5394.86	7238.39	10387.30	10930.50	$F(3,132) = 55.66$*	0.549	< .001	< .001	< .001	< .001	< .001	1.000
CIEtest4	4800.71	6439.10	8140.80	9144.56	$F(3,132) = 19.43$*	0.291	< .01	< .001	< .001	< .10	< .01	1.000
CIEtest5	6440.81	6221.03	10485.00	9894.33	$F(3,132) = 22.95$*	0.328	1.000	< .001	< .001	< .001	< .001	1.000
CIEtest6	5212.32	6284.08	6748.65	10959.89	$F(3,132) = 34.61$*	0.428	< .10	< .05	< .001	1.000	< .001	< .001
CIEtest7	6133.92	7090.82	9315.75	11018.56	$F(3,132) = 28.94$*	0.383	0.202	< .001	< .001	< .01	< .001	0.100
CIEtest8	6170.80	6910.82	10084.90	10079.28	$F(3,132) = 28.40$*	0.378	0.529	< .001	< .001	< .001	< .001	1.000
CIEtest9	4783.37	7053.10	5943.70	10439.06	$F(3,132) = 45.16$*	0.495	< .001	0.103	< .001	0.191	< .001	< .001
CIEtest10	2946.49	7186.72	2961.95	11391.67	$F(3,132) = 71.05$*	0.609	< .001	1.000	< .001	< .001	< .001	< .001
CIEtest11	3717.02	7515.62	4430.75	9889.28	$F(3,132) = 48.06$*	0.511	< .001	1.000	< .001	< .001	< .01	< .001
CIEtest12	4066.32	8099.00	4026.60	10230.67	$F(3,132) = 42.67$*	0.481	< .001	1.000	< .001	< .001	< .05	< .001
CIEtest13	3368.00	8703.31	2613.55	10049.06	$F(3,132) = 68.00$*	0.598	< .001	1.000	< .001	< .001	0.324	< .001

$M_1 = 4885.05$, $M_2 = 7236.55$, $M_3 = 7232.93$, $M_4 = 10366.16$

Note. $N = 68$; * $p < .001$; description CIEtest items see Table 14.

Table A26

Group statistics for emotions combined analysis CH3

Item	CCT group	*N*	*M*	*SD*	*SE*
Motivation	Low CCT	136	0.31	1.01	.086
	High CCT	136	0.47	1.01	.087
Creativity	Low CCT	136	0.35	0.95	.081
	High CCT	136	0.37	0.93	.079
Comfort	Low CCT	136	0.37	1.17	.100
	High CCT	136	0.38	1.19	.102
Happiness	Low CCT	136	0.21	1.10	.094
	High CCT	136	0.29	1.13	.097
Anxiousness	Low CCT	136	0.40	1.07	.092
	High CCT	136	0.39	1.04	.089

Note. $N = 68$.

Table A27

Independent samples test for emotions combined analysis, t-test for equality of means CH3

						95% CI	
Item	*t*	*df*	*p*	*MD*	*SE*	*LL*	*UL*
Motivation	-1.322	270	.187	-0.162	0.122	-0.403	0.079
Creativity	-0.194	270	.846	-0.022	0.113	-0.245	0.201
Comfort	-0.051	270	.959	-0.007	0.143	-0.289	0.274
Happiness	-0.599	270	.550	-0.081	0.135	-0.347	0.185
Anxiousness	0.115	270	.909	0.015	0.128	-0.237	0.267

Note. $N = 136$.

Table A28

Descriptive data of combined analysis CH3

						95% CI	
TKI style	CCT group	*N*	*M*	*SD*	*SE*	*LL*	*UL*
Competing	Low CCT	136	5.60	3.33	0.285	5.04	6.17
	High CCT	136	5.19	3.32	0.285	4.63	5.75
Collaborating	Low CCT	136	6.01	1.91	0.164	5.69	6.34
	High CCT	136	5.87	2.06	0.176	5.52	6.22
Compromising	Low CCT	136	7.56	2.02	0.173	7.22	7.90
	High CCT	136	7.62	2.06	0.176	7.27	7.97
Avoiding	Low CCT	136	6.61	1.96	0.168	6.28	6.94
	High CCT	136	6.81	1.94	0.167	6.48	7.14
Accommodating	Low CCT	136	4.46	3.02	0.259	3.94	4.97
	High CCT	136	4.75	2.83	0.243	4.27	5.23

Note. $N = 136$.

Table A29

Summary tests of between-subjects effects TKI styles high CCT versus low CCT CH3

TKI style	*SS*	*df*	*MS*	*F*	*p*
Competing	11.529	1	11.529	1.043	.308
Collaborating	1.471	1	1.471	0.373	.542
Compromising	0.235	1	0.235	0.057	.812
Avoiding	2.680	1	2.680	0.706	.402
Accommodating	5.882	1	5.882	0.687	.408

Note. N = 136.

Table A30

Tests of Normality VL1

	Shapiro-Wilk		
Item	Statistic	*df*	Sig.
Beautiful_Ugly_CW_diff	.982	95	.228
Beautiful_Ugly_RD_diff	.983	95	.246
Glare_NonGlare_RD_diff	.978	95	.106
Glare_NonGlare_CW_diff	.986	95	.423
Visuallywarm_Visuallycool_CW_diff	.976	95	.077
Visuallywarm_Visuallycool_RD_diff	.986	95	.432
Dislike_Like_RD_diff	.978	95	.120
Dislike_Like_CW_diff	.986	95	.391
Pleasant_Unpleasant_CW_diff	.986	95	.391
Pleasant_Unpleasant_RD_diff	.978	95	.120
Hazy_Clear_RD_diff	.989	95	.636
Hazy_Clear_CW_diff	.980	95	.165
Public_Private_RD_diff	.986	95	.442
Public_Private_CW_diff	.966	95	.014
Confined_Spacious_RD_diff	.989	95	.591
Confined_Spacious_CW_diff	.929	95	<.001
Relaxing_Tense_RD_diff	.989	95	.623
Relaxing_Tense_CW_diff	.959	95	.005
Bright_Dim_RD_diff	.990	95	.700
Bright_Dim_CW_diff	.979	95	.125
Stimulating_Subduing_RD_diff	.976	95	.074
Stimulating_Subduing_CW_diff	.984	95	.314
Ordinary_Special_RD_diff	.987	95	.500
Ordinary_Special_CW_diff	.984	95	.324
Cluttered_Uncluttered_RD_diff	.980	95	.160
Cluttered_Uncluttered_CW_diff	.987	95	.478

Note. N = 95; CW = Cold_Warm; RD = Room_daylight; diff = difference.

Table A31

Tests of Normality VL2

Item	Shapiro-Wilk		
	Statistic	*df*	Sig.
Beatiful_Ugly_CW_diff	.954	106	<.001
Beatiful_Ugly_RD_diff	.960	106	.003
Glare_NonGlare_CW_diff	.955	106	.001
Glare_NonGlare_RD_diff	.973	106	.029
Visuallywarm_Visuallycool_CW_diff	.892	106	<.001
Visuallywarm_Visuallycool_RD_diff	.911	106	<.001
Dislike_Like_CW_diff	.935	106	<.001
Dislike_Like_RD_diff	.922	106	<.001
Pleasant_Unpleasant_CW_diff	.929	106	<.001
Pleasant_Unpleasant_RD_diff	.903	106	<.001
Hazy_Clear_RD_diff	.976	106	.052
Hazy_CW_difflear_CW_diff	.958	106	.002
Public_Private_CW_diff	.916	106	<.001
Public_Private_RD_diff	.976	106	.056
Confined_Spacious_CW_diff	.942	106	<.001
Confined_Spacious_RD_diff	.930	106	<.001
Relaxing_Tense_CW_diff	.897	106	<.001
Relaxing_Tense_RD_diff	.967	106	.009
Bright_Dim_CW_diff	.968	106	.011
Bright_Dim_RD_diff	.983	106	.190
Stimulating_Subduing_CW_diff	.882	106	<.001
Stimulating_Subduing_RD_diff	.976	106	.050
Ordinary_Special_CW_diff	.987	106	.372
Ordinary_Special_RD_diff	.974	106	.039
Cluttered_Uncluttered_CW_diff	.983	106	.179
Cluttered_Uncluttered_RD_diff	.984	106	.241

Note. N = 106; CW = Cold_Warm; RD = Room_daylight; diff = difference.

Table A32

Frequency distribution of preferences in virtual spaces VL2

Item	Prefer very strongly (-3)		-2		-1		Neutral (0)		1		2		Prefer very strongly (3)	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
No shadows / shadows	2	1.9	7	6.6	3	2.8	10	9.4	33	31.1	35	33.0	16	15.1
Ceiling above / sky above	3	2.8	7	6.6	6	5.7	13	12.3	4	3.8	17	16.0	56	52.8
No daylight / daylight	1	0.9	1	0.9	4	3.8	4	3.8	8	7.5	29	27.4	59	55.7
No local daylight / local daylight	22	20.8	30	28.3	17	16.0	10	9.4	9	8.5	13	12.3	5	4.7
No weather / weather simulation	2	1.9	6	5.7	11	10.4	4	3.8	11	10.4	21	19.8	51	48.1
No local weather / local weather simulation	34	32.1	25	23.6	13	12.3	16	15.1	8	7.5	7	6.6	3	2.8
Cloudy sky / sunny sky	1	0.9	1	0.9	3	2.8	13	12.3	5	4.7	23	21.7	60	56.6
No realistic lighting / realistic lighting	0	0	3	2.8	2	1.9	6	5.7	12	11.3	35	33.0	48	45.3

Note. N = 106.

Acknowledgements

I am grateful to the many people who supported me in completing this work. I would like to extend my special thanks to Prof. Dr. Thomas Lachmann, Prof. Dr. Tandra Ghose, and Prof. Dr. Lothar Winnen for their valuable support and supervision. Additionally, I would like to acknowledge the contributions of other individuals, particularly Prof. Dr. Michael Dinkel for his initial support to launch this research, Dr. Ann-Kathrin Beck for her scientific and emotional support during the final year, and Dr. Matthias Heyck for his administrative support throughout my entire PhD period.

I am also grateful to my employers, *DHBW Cooperative State University Baden-Wurttemberg Mannheim* and *SRH Fernhochschule – The Mobile University*, for enabling me to combine research with university teaching and supporting my academic career. Furthermore, I extend my thanks to *allseated GmbH*, *Lite-Tech Veranstaltungstechnik GmbH*, and *mac. brand spaces GmbH* for their support in providing lighting technologies and virtual content for my studies.

Finally, I want to express my heartfelt gratitude to my family and friends for accompanying me on my journey of academic and personal development.

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Hiermit versichere ich,

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