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New Model for VDT Associated Visual Comfort in Office Spaces

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Content

Kurzfassung

Es existieren viele Studien über die Vitalität des Tageslichts für die menschliche Gesundheit und Wohlbefinden, zum Beispiel über Tageslicht verbundene physiologische und psychologische Funktionen wie Fertilität und Stimmung, sowie den Produktionszyklus vieler Hormone und Enzyme, die mit dem Tageslichtzyklus verbunden sind [29]. Gemäß dieser Tatsache und aufgrund der heutigen Lebensweise, in der die Menschen den größten Teil ihres Tages am Arbeitsplatz verbringen, ist der Einsatz von so viel Tageslicht wie möglich in den Arbeitsräumen von entscheidender Bedeutung. Zur Steigerung der Tageslichtnutzung in den Räumen ist es erforderlich, dessen Qualität zu steigern, weshalb diesbezüglich der mit Tageslicht verbundene visuelle Komfort eine wichtige Rolle spielt. Visueller Komfort hat verschiedene Aspekte, die in Kapitel-2 erklärt werden; derjenige, der im Rahmen dieser Studie untersucht wurde, ist die Schleierblendung. Die Schleierblendung ist ein Gesichtspunkt des visuellen Komforts, der üblicherweise in der Tageslichtplanung unterschätzt worden ist. Da heutzutage die Bildschirmarbeit zu den allgemeinen Aufgaben in Büros gehört, sollte die Schleierblendungsverhinderung auf den Bildschirmen deutlich in der Licht- und Raumplanung berücksichtigt werden. Schleierblendung ist die reflexionsverbundene Kontrastminderung, denzufolge das Kontrastverhältnis des visuellen Ziels unter einen erforderlichen Wert fällt und zu der Abnahme der Sichtbarkeit/Lesbarkeit des Ziels führt. Obwohl die letzten Technologieentwicklungen von TFT-LCD Bildschirmen das Problem reduziert, stellt immer noch schlechte Bildschirmsichtbarkeit durch Lichtreflexion ein aktuelles Problem dar, dass den visuellen Komfort und die Sehleistung negativ beeinflusst. Die wichtigste Motivation zur Durchführung einer Studie über Schleierblendung ist ein Verfahren zu entwickeln, das für die folgenden Ziele verwendbar wäre:

- Verbesserung des Entwurfs und der Gestaltung der Räume mit Bildschirmarbeitplätzen zur Verbesserung des visuellen Komforts und der visuellen Leistung.
- Verbesserung der Tageslichtplanungsstrategien für Räume mit Bildschirmgeräten, die zu weniger Energieverbrauch beitragen könnten.
- Verbesserung der Fassadensysteme, die für Räume mit Sehaufgaben am Bildschirm gedacht sind, indem der Aspekt der Schleierblendung in deren Designstrategie berücksichtigt wird.

Gemäß den bestehenden Empfehlungen kann durch die Kontrolle der durchschnittlichen Helligkeit der Fenster die Qualität der Bildschirme in Bürogebäuden gesteuert werden [72]. In Kapitel-3 wird ein Bewertungsverfahren unter Verwendung der Ergebnisse einer

Nutzerakzeptanzstudie durchgeführt, um die Beziehung zwischen subjektiver Bewertung von Bildschirmqualität und verschieden potentiellen Einflussfaktoren, wie Fensterleuchtdichte zu untersuchen. Die Ergebnisse zeigen, dass sich bestehende Empfehlungen zur Begrenzung der Fensterleuchtdichte nicht eignen, um die Bildschirmqualität zu bewerten, außerdem ist das Lichtniveau auf dem Bildschirm (gemessene Beleuchtungsstärke an der Bildschirmecke) auch kein angemessener Bewertungsmaßstab für Bildschirmqualität. Dies betont den Bedarf eines neuen Verfahrens, mit dem die Bildschirmqualität an den Arbeitsplätzen bewertet werden kann. Die Ergebnisse zeigen auch, dass die Schleierblendung ein gutes Kriterium hierfür sein könnte, da zwischen den Nutzerbewertungen und dem primär entwickelten kontrastbasierten Schleierblendungsfaktor ein Zusammenhang besteht. Diese Studie zeigt den Bedarf weiterer Forschung über Kontrastbasierte Schleierblendung um einen geeigneten Prüfstein zur Bewertung der Bildschirmlesbarkeit zu beschaffen.

Nach der Feststellung, dass ein Kontrastverbundenes Modell, eine geeignete Methode für die Bewertung der Bildschirmqualität sein könnte, ist nächste Schritt die Zuverlässigkeitsanalyse der existierten Kontrast-Modelle als Grundlage für die Kontrastminderungsauswertungen. Das letzte Standard-Modell für die Kontrastanforderung für die Bildschirm-Sehaufgabe ist in ISO 9241-303:2008 (Anhang D) angegeben [36] und basiert auf Kokoschkas Schwellenkontrast-Modell (Kapitel-2). Zur Bewertung der Zuverlässigkeit des genannten Kontrastmodells werden zwei verschiedene Nutzerakzeptanz Studien durchgeführt:

- Ein Landolt-Ring Identifikationstest
- Eine Leseaufgabe

Der Landolt-Ring Test basiert auf einem Standardtest für augenärztliche Untersuchungen, mit der Aufgabe der Identifizierung der Schlitz-Ausrichtung in den Landolt-Ringen. Der definierte Kontrast der Landolt-Ringe in dieser Studie ist sehr niedrig und nahe dem Schwellenkontrastwert. Die Ergebnisse werden ausgewertet, um herauszufinden, ob die subjektive Kontrastwahrnehmung zu dem Standard-Schwellenkontrastmodell passen könnte oder nicht (Kapitel-4). Laut dieser Studie passt die durch Nutzerbewertung bestimmte Identifikationswahrscheinlichkeit nicht optimal an den geschätzten Wert durch das Schwellenkontrast-Modell. Die erzielte Uneinigkeit ist von erheblicher Bedeutung für die ältere Altersgruppe. Dies deutet darauf hin, dass zu dem Kontrast Modell von ISO-Norm weitere Untersuchungen notwendig wären. Eine zweite Nutzerakzeptanz Studie wurde entwickelt, um die bestehenden Kontrast Modelle (ISO-Norm-Modell und ein andere Kontrast-Modell von

Poynter 58, 59) zu bewerten. Diese experimentelle Studie basiert auf einer Leseaufgabe, die einer Routine Büroaufgabe entspricht (Kapitel-5). Die jeweilige Leseaufgabe basiert auf Leserate/Geschwindigkeit mit dem Konzept, dass die Nutzer ihre beste Leserate erreichen, wenn der Aufgabekontrast hoch genug ist. Das Verfahren ist so konzipiert, dass zuerst die persönliche Leserate mit hohem Aufgabenkontrast (schwarze Schrift auf weißem Hintergrund) gemessen wird, um dann den Aufgabenkontrast auf den niedrigsten Kontrastwert zu reduzieren, unter dem die Benutzern immer noch mit ihren persönlichen Leserate lesen können. Diese Studie hat einen zweiten Teil, um den Komfort des Probanden bei verschiedenen Kontrastwerten zu dokumentieren. Die Ergebnisse dieser Studie werden mit den bestehenden Kontrastmodellen verglichen und die Schlussfolgerung ist, dass es eine schwache Korrelation zwischen der Kontrastwahrnehmung/ Präferenz der Nutzern und sowohl der ISO-Norm als auch dem Poynter-Modell besteht.

Nach der Schlussfolgerung, dass die bestehenden Modelle nicht ideal zu den Kontrastwahrnehmungen/Präferenzen der Nutzer bei der Bildschirmsehaufgabe passen, wird beschlossen ein neues Modell, das den beobachteten Daten besser entspricht zu entwickeln (Kapitel-6). Laut der Bewertung der Beobachtungsdaten in allen Altersgruppen, ist es eindeutig, dass der Alterseinfluss auf Kontrastwahrnehmung/Präferenz deutlich geringer ausfällt als es die empfohlenen Werte des ISO-Norm-Modells vorgeben. Gemäß den Auswertungen, ist die neue Alterseinwirkung wie folgt formuliert:

$$age \leq 30 \Rightarrow K_{age} = 1$$

$$age > 30 \Rightarrow K_{age} = age \cdot 0.0025 + 0.925$$

Basierend auf den erzielten Beobachtungsdaten und nach der Modellstruktur des ISO-Norm Kontrastmodells, wird ein neues Modell für den erforderlichen Mindestkontrast MRC an Bildschirmgeräten entwickelt. Dieses Modell ist eine Funktion des Alters, des dunklen Zustands (niedrige Leuchtdichte) und der durchschnittlichen Umfeldleuchtdichte und umfasst die folgenden zwei Konzepte für die Kontrastanforderung:

- Erforderlicher Kontrast für gute Lesbarkeit (unterstützt nicht unbedingt Komfortlesen).
- Erforderlicher Kontrast für Komfortlesen.

Das neue Modell umfasst auch zwei verschiedene Text-Polaritäten, den positiven und negativen. Dieses Modell lautet wie folgt:

$$\frac{MRC}{K_{age}} = 1.1 + 0.33 \cdot CF + 0.37 \cdot PF + 16.2 \cdot \left(\frac{L_E^{\ 0.41}}{L_L^{\ 1.54}} \right)$$

CI: Komfortindex =

0 für gute Lesbarkeit
1 für Komfortlesen

PI: Polaritätsindex =

0 für positive Polarität
1 für negative Polarität

Die Wirkung des Dunkelzustands ist bedeutender als andere Faktoren und zeigt, dass das wichtigste Phänomen bei der Kontrastanforderung der Wert der niedrigeren Leuchtdichte auf die Sehaufgabe ist. Es sollte erwähnt werden, dass obwohl das MRC-Modell für alle Werte niedrigerer Leuchtdichte (L_L) entwickelt wurde, aber laut der typischen Helligkeit in dem Geltungsbereich der Studie gibt es nur wenige Beobachtungen mit sehr niedrigen Werten der L_L. Da der niedrige L_L Wert einen hohen Kontrastbedarf ergibt, existieren nur wenige Daten im Datensatz mit sehr hohen Kontrastanforderungswerten (höher als 10). Dies könnte einen Ausblick für zukünftige Untersuchungen geben, indem weitere Benutzerbewertungen unter niedrigen L_L Werten durchgeführt werden, um mehr Betrachtungen über hohe Kontrastanforderungen zu erhalten. Diese Untersuchungen könnten zu einer Verbesserung des MRC-Modells führen.

Das grundlegende Konzept dieser Studie ist es eine Methode anzubieten, die zur Verbesserung der Beleuchtung und Gestaltung der Büroflächen (oder jede andere Raum mit der Bildschirmsehaufgabe) angewendet werden kann. Dafür ist es notwendig für die betrachteten Fälle Simulationsstudien durchzuführen. Die Simulationsstudien im Rahmen dieser Forschung basieren auf dem Licht-Simulationsprogramm, RADIANCE, das ein genaues Programm für die Bewertung der Beleuchtungsfaktoren innerhalb der Räume ist. Eine wichtige Voraussetzung zur Durchführung einer genauen Simulationsstudie diesbezüglich ist ein präzises Material-Modell für den Bildschirm. Aus diesem Grund wird innerhalb dieses Forschungsvorhabens ein Messverfahren durchgeführt um die Materialeigenschaften eines VDT Typs -Eizo FlexScan L565(der angewandte Bildschirm für alle genannten Nutzerakzeptanzstudien)- zu messen (Kapitel-7). Der Messvorgang wird durch ein Gerät mit der Bezeichnung Gonio-Photometer durchgeführt. Das ziel ist es, die Reflexionseigenschaften des Monitors für alle möglichen Einfallswinkel des Lichts zu bestimmen. Nach Erhalt der Reflexionseigenschaften (BRDF Daten) des Materials für jeden Einfallswinkel, wird ein Modellierungsverfahren durchgeführt, um ein RADIANCE-Material zu generieren, das den gemessenen Reflexionseigenschaften entspricht. Nach dem Erstellen eines Bildschirmmodells mittels der erhaltenen Messergebnisse, werden zum Vergleich zwei weitere

Modelle herangeführt, die mit unterschiedlichen Messmethoden ermittelt wurden. Diese Vergleichsstudie wird durchgeführt, um darzustellen wie das Materialmodell die Einschätzung der Bildschirmlesbarkeit (und die weitere darauf basierende Entscheidungen) beeinflussen könnte.

Nach dem Erstellen eines zuverlässigen Kontrastmodells und eines genauen Materialmodells für eine optische Anzeige, wird eine Simulationsstudie für einen Beispiel-Büroraum durchgeführt (siehe Kapitel-8). Das Ziel ist es, verschiedene Parameter zu variieren, um die bestmöglichen Optionen mit der geringstmöglichen Schleierblendung auszusuchen. Diese Simulationsstudie ist für ein Standardbüro in Freiburg im Breisgau (Deutschland) mit zwei verschiedenen Fenstergrößen, mit und ohne Jalousien und mit acht möglichen VDT Orientierungen durchgeführt. Daher, gibt es 24 verschiedene Varianten, für die die jährliche Simulationsstudie durch DAYSIM (RADIANCE-basiertes Programm für jährlichen Lichtsimulationen) durchgeführt wird. Die Reflexionswerte auf dem Bildschirm werden in stündlichen Zeitschritten für das ganze Jahr berechnet. Gemäß dem erzielten jährlichen Reflexions-Profil für jede Variante und die getroffenen Annahmen für niedrige und hohe Leuchtdichte des Anzeigebilds, wird das jährliche Profil des relativen Kontrastmangels für jede Variante wie folgt berechnet:

$$if \quad CR < MRC \Rightarrow RCD = \frac{(MRC - CR)}{MRC}$$

CR: Kontrastverhältnis zwischen hoher und niedriger Leuchtdichte des Displaybildes (Reflexionsberücksichtigt)

RCD: relativer Kontrastmangel um den Schleierblendungsgrad auszudrücken

Um einen Vergleich zwischen allen 24 Varianten zu schließen, werden die berechneten RCDs über den ganzen Bildschirm an jedem Zeitschritt ermittelt (RCD_M) und die folgenden Kriterien berechnet:

- Der Anteil des Jahres mit Kontrastmangel-Problem
- Der Jahresdurchschnitts Wert der RCD
- Der Maximalwert des RCDM während des ganzen Jahres

Auf Basis der oben genannten Kriterien werden die Ratenfaktoren (R_F) für alle 24 Varianten berechnet, die gleich der Multiplikation aller drei Kriterien sind und die Güte der Variante in Bezug auf die Schleierblendung aufzeigt. Die Ergebnisse dieser Studie zeigen, dass in den untersuchten Büroräumen (Einzel-Büro, Südfenster, in Freiburg), die Varianten mit Jalousie in der Regel die bestmöglichen Varianten sind mit geringstmöglichen Problemen. Die Ergebnisse zeigen auch, dass für diese Büroausrichtung, der Jahreszeitraum von Oktober bis März den kritischsten Zeitraum darstellt, währenddessen die Verwendung der Jalousien für eine gute Bildschirmlesbarkeit notwendig ist. Der andere Punkt ist, dass die Verringerung der Größe des Verglasungsbereichs weniger Einfluss auf die Verringerung der Schleierblendung hat als das Aufbringen eines Verschattungssystems wie die Jalousie. Auch die besten VDT- Orientierungen bezüglich zum Fenster sind von der Fenstergröße und des Verschattungssystems abhängig, weshalb keine eindeutig beste Option ermittelt werden kann. Daher ist es um Vorschläge für jeden Büro-Typ abzugeben notwendig, mehrere Simulationen und eine Vergleichsstudie zwischen allen Ergebnissen durchzuführen.

Um das Verfahren der Ermittlung der RCD-Werte, die in verschiedenen Schritten durch die Verwendung mehrerer Programme, d.h. DAYSIM, OCTAVE und AWK umgesetzt werden soll zu vereinfachen, ist ein Computer-basiertes Tool entwickelt worden, das den gesamten Prozess über die Konfiguration eines Skripts ermöglicht. Dieses Tool ist mit C++ programmiert und basiert auf RADIANCE und DAYSIM Programmen und kalkuliert die RCD-Werte für eine definierte Beleuchtungssituation oder Erzeugt ein jährliche RCD-Profil für das ganze Jahr. Eine wichtige Perspektive für die zukünftige Entwicklung hinsichtlich des Bewertungstools wäre die Verbesserung des Tools für öffentliche Anzeigetafeln (Anzeigen in öffentlichen Orten wie Flughäfen). Das bedeutet, dass das Tool so modifiziert werden kann, dass anstelle der Kalkulation des Kontrastmangel-Profils von einem einzigen Aussichtpunkt, diese Schätzung für viele Aussichtspunkte durchgeführt wird. Diese Schätzung könnte auch hinsichtlich einer Gewichtungsfunktion von Aussichtpunktverteilungsordnung erstellt werden. Dieses Tool wäre für den Erhalt folgender Ergebnisse geeignet:

- Die beste Position für die Platzierung der Anzeige an öffentlichen Orten, um die bestmögliche Sichtbarkeit aus allen möglichen Blickwinkeln herzustellen.
- Der beste Neigungswinkel der Anzeige, der durch ein motorisiertes System kontrolliert werden könnte, das nach der geschätzten Schleierblendung im Bezug auf das Lichtverhältnis und der Aussichtpunktverteilungsordnung programmiert wird.

Executive summary

There are many studies regarding the vitality of daylight in human health and well-being, for instance the daylight related physiological and psychological functions like fertility and mood and the cycle production of many hormones and enzymes which are related to the cycles of daylight [29]. According to this fact and due to today's lifestyle, in which people spend the greatest part of their daytime at work, employing as much daylight as possible inside the work spaces is of vital importance. For increasing the daylight use inside the rooms it is required to improve the quality of daylighting and a significant factor in this regard is the daylight-related visual comfort. Visual comfort has different aspects which are explained in chapter-2; the one which is to be evaluated within the scope of this study is called veiling glare. Veiling glare is the aspect of visual comfort which has been usually underestimated in daylighting design.

Nowadays the common tasks in offices are computer based. Avoiding veiling glare on visual displays shall noticeably be considered in lighting/space design. Veiling glare can be defined as the reflection-associated contrast-reduction due to which, the contrast of the visual target falls below the required value, causing difficulty in visibility or readability of the target. Although the recent technology development of TFT-LCDs has reduced this problem bad screen-visibility due to reflection is a problem affecting visual comfort and visual performance. The most important motivation for conducting research on veiling glare is to develop a method to estimate reflection associated with the visual quality of visual displays in the relevant spaces, which would be applicable to the following objectives:

- Improvement of the design/layout of the spaces enclosing visual display to provide better visual comfort and performance.
- Improvement of daylighting design strategies for the spaces with visual display (more comfortable daylighting design), which could result in less energy consumption.
- Improvement of the advanced façade systems intended for spaces with onscreen visual tasks, by considering this aspect of visual comfort in their design strategy.

According to the standards, by controlling the average luminance of the windows we can control the quality of the visual displays in office buildings [72]. In chapter 3, the results of a user assessment study are used to evaluate the relationship between subjective rating of screen quality and various potential estimation-factors such as window-luminance. The results of this study exhibit that in spite of the existing recommendations, window luminance cannot be a good criterion for estimating the screen quality; furthermore based on this study, the light level on the screen (illuminance measured at screen corner) is also not an indicator for screen quality. Therefore a new principle would be necessary to evaluate the visual displays in the office spaces. Based on the same study, there exists a relationship between the user assessments of the display and a primary factor developed for veiling glare based on contrast. This study shows the importance of further investigation on contrast-associated veiling glare in order to derive an appropriate criterion for estimating screen-visibility.

After concluding that a contrast related model could be an appropriate method for rating the screen quality, the next step is analyzing the reliability of the existing contrast models as the basis for contrast evaluation. The recent standard model for contrast requirement on visual displays is stated on ISO 9241-303:2008 (Annex D) [36] and is developed based on Kokoschka's contrast threshold model (see chapter-2). To assess the reliability of the mentioned contrast model two various user assessment studies are conducted:

- A Landolt ring identification test
- A Reading test

Landolt ring test is based on a standard test for ophthalmologic examination, which includes the identification of the gap-orientation in the Landolt rings. The defined contrast of the Landolt rings within this study is very low and close to contrast threshold value. The results of the tests are evaluated to determine whether or not the subjective contrast perception would fit the estimation by the standard contrast-threshold model (Chapter-4). According to this study the probability of identification, as determined by user assessment does not match well to this probability as predicted by the threshold-model. The achieved disagreement is more considerable for the older age group. This indicates that the ISO- standard contrast model would certainly need more investigation.

A second user assessment study is designed to evaluate the existing contrast models (ISO-standard model and another model developed by Poynter [58, 59]) and to develop a new model for required contrast on visual displays if necessary. This experimental study is defined based on a reading task which is a routine office task. The respective reading task is designed based on reading-rate or reading-speed (chapter-5). The concept is that the individuals have their best reading-rate when the task-contrast is high enough. The procedure is thus – that the first personal reading rate is measured with high task contrast (black letters on white background) and then the task contrast is reduced to determine the lowest contrast value under which the users can still read with their personal reading rate. This study has a second part to record the comfort of the subjects at different contrast levels. The results of this study are compared to the existing contrast models. The conclusion is that there is a poor correlation between the contrast perception/preference derived by the user assessments and both ISO-standard and Poynter models.

After concluding that the existing models do not appropriately predict the contrast perceptions and preferences of the users while conducting onscreen visual task, it is decided to develop a new model which fits better to the observed data (chapter-6). After evaluating the observational data in all age groups, it becomes clear that age influence on contrast perception/preference is of significant less value than considered value in the ISO-standard model. According to the performed evaluations, the new age effect is formulated as:

$$age \leq 30 \Rightarrow K_{age} = 1$$

$$age > 30 \Rightarrow K_{age} = age \cdot 0.0025 + 0.925$$

Based on the achieved observational data and according to the model-structure of ISO-standard contrast model, a new model for -minimum required contrast MRC- on visual display is developed. This model is a function of age, low state luminance and average environmental luminance and involves the following two concepts for contrast requirement:

- Required contrast for good readability (doesn't necessarily support the comfort reading).
- Required contrast for comfort reading.

The new model also covers two different text polarities- positive and negative text polarities. This model reads as follows:

$$\frac{MRC}{K_{age}} = 1.1 + 0.33 \cdot CF + 0.37 \cdot PF + 16.2 \cdot \left(\frac{L_E^{\,0.41}}{L_L^{\,1.54}} \right)$$

CI: Comfort index =
0 for good readability
1 for Comfort reading

PI: Polarity index =
0 for positive polarity
1 for negative polarity

The effect of low state luminance is more significant than other factors, which indicates that the most important phenomenon in contrast-requirement is the value of lower luminance on the visual task. It should be mentioned that although the MRC model is developed for all values of low state luminance (L_L), according to the typical brightness within the scope of this study, there are only few observations with very low value of L_L. As low value of L_L results in high required contrast, therefore there is little data in the dataset with very high contrast requirements (higher than 10). This could provide an outlook for further investigation in future i.e. conducting additional user-assessments under the conditions which afford very low values of L_L to avail more observations with high contrast-requirement. This investigation could help improve the MRC model.

The main concept of this study is presenting a method to be applied for improving the lighting/layout design of the office spaces (or any other space including onscreen visual task). For this purpose it is necessary to perform simulation studies for the under-study cases. The simulation studies within the scope of this research are based on the lighting simulation program, RADIANCE, which is an accurate program for estimating the lighting-related factors inside the spaces. An important requirement for performing an accurate simulation study in this respect is availing a precise material model for visual display. For this reason, within this research project a measurement process is performed for a VDT screen type "Eizo FlexScan L565" which is the same screen used for all mentioned user-assessment studies (chapter-7). The measurement procedure is conducted by means of a device called gonio-photometer. The purpose of the measurement is to determine the reflection characteristics of the screen for all possible angles of incident lights. After achieving the reflection properties (BRDF data) of the material for all incident angles, a modeling procedure is conducted to make a RADIANCE-material model that resembles the measured reflection-characteristics. After modeling the visual display based on performed measurements, the developed material-model and two other models from the same display based on two other measurement methods are applied in a comparative study. This comparative study is carried out to present an example of how the material model could affect the estimation of screen visibility (and further decisions based on the estimation). According to the conclusions of the comparative study, the process of measuring and modeling the material of a visual display could lead to an entirely different outcome.

After achieving a reliable contrast-model and a precise material-model for a visual display, a simulation study of an example office space is performed (see chapter-8). The aim is to vary the various parameters of the office to find the best possible options with the less possible veiling-glare problem. This simulation study is conducted for an office located in Freiburg, Germany with two different window-sizes, with and without venetian blinds and with eight possible VDT orientations. Thus, in general there are 24 different variants, for which annual simulation studies during the standard year are performed by means of DAYSIM (RADIANCE-based program for annual lighting simulations). The reflection luminances on the computer screen are computed in hourly time-steps throughout the year. According to the achieved annual reflection profile for each variant and by making initial assumptions for low and high state luminance of display images, the annual profile of relative-contrast-deficiency for each variant is computed as:

$$if \quad CR < MRC \Rightarrow RCD = \frac{(MRC - CR)}{MRC}$$

CR: contrast ratio between high and low state luminance of display image (taken reflection into account)

RCD: relative contrast deficiency to express the veiling glare magnitude

For making a comparison between all 24 variants, the computed RCDs all-over the screen at each time step are averaged (RCD_M) and the following criteria are computed:

- Fraction of year with contrast deficiency problem
- Annual average value of RCD
- Maximum value of RCD_M throughout the year

Based on all above mentioned criteria the rating factors (R_f) are computed for all variants which are equal to the multiplication of the all three criteria. The computed rating factor indicates the goodness of each variant. The results of this study exhibit that in the observed office room (single office, south facing window, in Freiburg) the variants with venetian blinds are in general the best options with fewer possible problems. The results also show that for this office orientation, the year-period from October to March is the most problematic period, during which using venetian blinds is necessary to provide a good screen-visibility. The other point is that reducing the size of the glazing-area has less influence on decreasing the veiling-glare than applying a shading system like venetian blinds. Also the best VDT orientations relative to window are dependent on the window-size and shading-system, and there is no absolute best option. Therefore in providing suggestions for any office type, it is necessary to perform several simulations and a comparative study between all results.

In order to simplify the procedure of deriving RCD values which shall be implemented in various steps by using several programs i.e. DAYSIM, OCTAVE and AWK, a computer based tool is developed which makes the whole process possible via configuration of a script. This tool is programmed by C++ and is based on RADIANCE and DAYSIM programs to compute the RCD values for

one lighting case and/or generating an annual RCD profile for the whole year.
One important consideration for future development regarding the evaluation tool would be improving the tool to be used for the public displays (displays used in public places like airports). That means the tool could be modified so that instead of predicting the contrast-deficiency-profile from a single viewpoint, it could make this prediction from several viewpoints. This estimation could be regarding a weighting function to account for the viewpoints-distribution-order. This tool would be applicable to derive the following results:

- The best position for placing the display in the public-space for affording the best possible visibility from all potential viewpoints.
- The best declination angle of the display which could be controlled by a motorized system programmed according to the predicted veiling glare based on lighting condition and viewpoints-distribution-order.

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1 Introduction

1.1 Motivation

“Daylight is playing a significant role in achieving quality of life and comfort in buildings. There is ample evidence that access to windows affects mood motivation and productivity at work, through reduced fatigue and stress.” [37 referred to 29]. To support a wide daylight usage in the buildings, it is necessary to pay attention to the quality of daylighting inside spaces. There are different factors which shall be taken into consideration for this quality improvement such as brightness, color rendering index, contrast and visual comfort. One significant reason, according to which the individuals are willing to prevent the incoming daylight from windows, is that they don’t feel visually comfortable in the presence of daylight inside the room. The visual discomfort associated with daylight mostly results in covering of the glazing area (by shading devices, curtains, etc.) and providing the required light via artificial sources. The consequence would be more energy consumption and less healthy and ergonomic environments based on the fact that the resulting daylight-deficiency could disturb the mood, fertility and the normal rhythm of the occupants.

In spaces such as office rooms that involve onscreen visual tasks, a significant aspect of visual discomfort is related to the visual quality of computer screens. When the occupants are disturbed by daylight related reflection on their visual displays, they often close the blinds or curtains and turn on the lamps; this means that due to the screen-visibility-problem the occupants might not benefit from a day-lit space with all its advantages. To avoid this inconvenience it is necessary to consider visual quality of visual displays as an important subject in quality of design. This aspect of visual discomfort has been usually undervalued in the design process (including room, layout and lighting design) of spaces such as offices or other relevant spaces.

Inconvenient visual quality caused by working with computer screens could be of more significance in big office rooms with large glazing areas and more occupants, which afford less flexibility to change the on hand furnishings. Nevertheless, by being aware of visual quality of the applied visual displays under different lighting conditions, it is possible to control many potential undesired situations in advance and in the design phase. For this purpose, it is necessary to achieve a reliable basis and method for predicting the visual quality of the intended visual displays under desired lighting conditions. This will be the focal point of the current research study.

Therefore and according to above descriptions, the underlying reasons for the essentiality of such a study can be summarized in the following points:

- Most tasks in office spaces are computer based.
- Employing as much daylight as possible is desired inside the spaces.
- In order to encourage a wide daylight-usage in office spaces, computer screens must sustain a good visual quality under daylight conditions.
- A reliable method is required to evaluate the visual quality of computer screens that could be applied in the design phase in order to prevent the potential undesired situations in advance.

1.2 Objectives

The main objective of this Ph.D. thesis is to propose an appropriate method for evaluating visual quality of computer screens in office spaces. Photometrical quality of different visual displays is not within the scope of this research study. The concept of visual quality in this research relates to the application of the displays inside office spaces (or other relevant spaces) under diverse lighting conditions. For providing good and comfortable screen-visibility under any lighting condition, too much light reflection on the screen should be avoided. Even though a visual display located in any lit space is confronted with the reflection of ambient lights and objects on its surface the reflection must be restricted in an acceptable range. This reflection is considered to be in acceptable range when it doesn't cause a phenomenon called veiling glare. Veiling glare is the contrast-reduction of a displayed image[1] due to reflection which impairs the visibility of the image (for more details see 2.3 Veiling glare).

The main question in this regard would be how to evaluate visual displays in order to estimate their reflection-related visual quality. The hypothesis in this Ph.D. for an appropriate evaluation method is "veiling glare evaluation method", which can be described with the following statement:
"Visual quality of computer screens in offices shall be evaluated by predicting the potential veiling glare on the screens that could occur under different lighting conditions"

As veiling glare is actually the reduction of image contrast this method can be also called "contrast deficiency evaluation method". In order to evaluate veiling glare or contrast deficiency it is necessary to use a value for "minimum required contrast" as the basis for predicting contrast deficiency. This means when the image contrast on the display is lower than the permitted minimum value, it is pointed as contrast deficiency.

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[1] Displayed Image is used here a g general concept which would also includes the displayed text.

According to the available standards the luminance value of the glazing area in the office rooms could determine the reflection related screen quality [72]. This idea is to be evaluated versus the hypothesis of this research. In general to test the described hypothesis the following procedure is to be conducted as the research strategy of this Ph.D.:

- An experimental study is performed to compare the user satisfaction of visual displays with both window-luminance (suggested criteria by standards) and veiling glare (hypothesis of this study). The purpose of this part is testing the relevance of veiling glare method.
- In case that the veiling glare method shows to be a relevant method, the second experimental study would be the assessment of the existing standard model for "minimum required contrast" as a basis for veiling glare study.
- In case that the standard model shows no reliability for veiling glare study on visual displays, the third experimental study would be developing a new model for minimum contrast required for working on visual displays.
- After finalizing the veiling glare evaluation method it will be implemented in the existing lighting simulation programs to facilitate simulation-based veiling glare study for any visual display located in any desired space.

1.3 General outline

This research study is conducted in seven main parts which are described as the following:

The first part of the current research study includes a review of the existing aspects of glare i.e. discomfort glare, disability glare and veiling glare. The concentration of this part is on veiling glare on visual displays which occurs due to reflection associated with contrast deficiency. For this reason, the standard models for evaluating contrast deficiency are also discussed in this section.

The second part comprises a pre-evaluation of veiling glare using the results of an already completed user assessment study (Chapter-3). In this part, the relationships between the subjective estimation of screen quality and different criteria are evaluated. A preliminary model of veiling glare is developed within this part to be compared with the available subjective results. Furthermore, other criteria which might be used to estimate the quality of visual display in office rooms are also evaluated against the available user assessment results.

In the third part, the existing standard model of contrast threshold is evaluated for onscreen visual tasks by designing a contrast test and comparing the subjective contrast perception with existing contrast threshold model (Chapter-4). The latest standard for minimum required contrast for visual displays is based on the contrast threshold. Hence the outcome of this study demonstrates whether the standard contrast model is an appropriate basis for estimating the contrast deficiency on computer screens or not.

In the fourth part, the aim is to design and perform a new user assessment test to evaluate the contrast perception /preference of test persons and to compare the subjective results with existing models for minimum required contrast for visual displays (Chapter-5).

The fifth part is the statistical evaluation of the obtained results from the user assessment study in the fourth part. The purpose of this part is to develop a new model for minimum required contrast that fits well to observational data of contrast perception/ preference.

In the sixth part, the intention is to develop a computer based model for evaluation of veiling glare (Chapter-7). This part consists of two major subparts, one part is measurement and modeling of a LCD material to be used in lighting simulation program, RADIANCE, and the second part is performing a simulation study to assess the effect of the modeling procedure of a screen material in simulation-based veiling glare prediction of the screen.

The seventh part is a simulation study to assess the application of the developed model in an example office room with different layouts. The purpose is presenting an example about the usage and convenience of the new method for optimizing an office design concerning less possible veiling glare throughout the year.

1.4 Background of the Thesis

This thesis is based on research work within the framework of a DFG (Deutsche Forschungsgemeinschaft) funded project entitled as „Ermittlung relevanter Einflussgrößen auf die subjektive Bewertung von Tageslicht zur Bewertung des visuellen Komforts in Büroräumen“ in the german language. The meaning is “evaluation of the relevant parameters on subjective estimation of daylight in order to evaluate the visual comfort in office rooms”.

The project was launched in 01.01.2008 and ended in 31.12.2010. The project-partners were “Fachgebiet Bauphysik und Technischer Ausbau (FBTA)” [sector of building-physics and technical construction], Department of

Architecture, Karlsruhe Institute of Technology (KIT) and Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg. The focus of the project has been the evaluation of the influence of various relevant criteria such as age, brightness, color, etc. on the subjective estimation of daylight in order to evaluate the visual comfort in office spaces. This project which is abbreviated with "QUANTA" has been conducted in two main parts, one part within the Fraunhofer ISE and the other one within FBTA. The part of Fraunhofer ISE included the user assessment studies in the office-like test-rooms which were performed in the daylight laboratory sited on the roof of the institute. The part of FBTA comprised the field studies i.e. the user assessment studies which were performed in the real office buildings. This Ph.D. thesis has been implemented within the part of the project which has been conducted at the Fraunhofer ISE.

2 Review of existing methods - Aspects of visual discomfort or glare

This chapter is a review of different aspects of glare with more focus on veiling glare which is to be studied within the scope of this research study. According to CIE, glare is defined as a vision condition which is concerned with discomfort or decreased ability to discern significant objects, or both, because of an inappropriate range or distribution of luminance or contrast [20].

Glare can be categorized in three different types i.e. discomfort glare, disability glare and veiling glare.

2.1 Discomfort glare

As stated by CIE, discomfort glare is a type of glare which cause discomfort without necessarily impairing the vision [20]. Discomfort glare is usually defined as a function of the main following four parameters (CIE 1983):

$$G = \left(\frac{L_s^a \cdot \omega_s^c}{L_b^d \cdot f(\theta)} \right) \quad (2\text{–}1)$$

L_s: source luminance in the field of view [cd/m²]
ω_s: solid angle subtended by the glare source [-]
Θ: angular displacement of the glare source from the observation's line of sight
L_b: general field luminance (background or ambient luminance) controlling the adaptation level of the observer [cd/m²]

In this equation the G is the discomfort glare factor expressing the subjective sensation and a, c and d are the weighting exponents.

In the following there is a list of the more commonly-used discomfort glare indices which have been developed at different times since 1950 up until recently:

- BRS or BGI glare equation [31]
- Daylight Glare Index (DGI) [17, 32]
- CIE Glare Index (CGI) [25, 26]
- Unified Glare Rating (UGR) [21]
- Visual Comfort Probability (VCP) [34]
- New Daylight Glare Index (DGIN) [56]
- Predicted Glare Sensation Vote (PGSV) [70, 69]
- Daylight Glare Probability (DGP) [83]

Between the above mentioned indices the DGP is the most recently developed daylight glare rating which unlike to the other indices has been developed under real daylight conditions. It describes the probability that a person is disturbed by daylight glare and is an empirical equation based on the vertical illuminance at eye level, source luminance, source solid angle and a position index [83]:

$$DGP = 5.87\cdot 10^{-5}\cdot E_v + 9.18\cdot 10^{-2}\cdot \log(1+\sum_i \frac{L_{s,i}^2\cdot \omega_{s,i}}{E_v^{1.87}\cdot P_i^2}) + 0.16 \qquad (2–2)$$

E_v: vertical eye illuminance [lux]
P: position index [-]
L_s: luminance of source [cd/m²]
ω_s: solid angle of source [-]

2.2 Disability glare

In CIE the disability glare is defined as a type of glare which impairs the vision. "It is caused by scattering of light inside the eye because of the imperfect transparency of the optical components of the eye, and to a lesser extent by diffuse light passing through the scleral wall or the Iris." The scattered light superimposes the image of objects on retina and results in reducing the contrast of the image on retina. This superimposing scattered light is called veiling luminance (L_{veil}) because the effect is comparable to viewing through a net curtain. The veiling luminance has a considerable effect on visibility when there are intense light sources in peripheral visual field and the objects to be seen has a low contrast. The contrast reduction due to veiling luminance may cause the contrast of an object to become lower than the threshold and therefore the object cannot be seen, or the contrast gets close to the threshold and therefore the object is difficult to see [23].

The value of veiling luminance is dependent on the intensity of the glare source and its distance from eye and the angle between the glare source and line of sight (see Figure 2–1).The Stiles-Holladay disability glare formula explains the veiling luminance as the following [23]:

$$\frac{L_{veil}}{E_{glare}} = \frac{10}{\theta^2} \qquad (2–3)$$

L_{veil}: veiling luminance [cd/m^2]
E_{glare}: illuminance at the eye caused by glare source [lux]
Θ: angle between direction of glare source and the line of sight [degree]

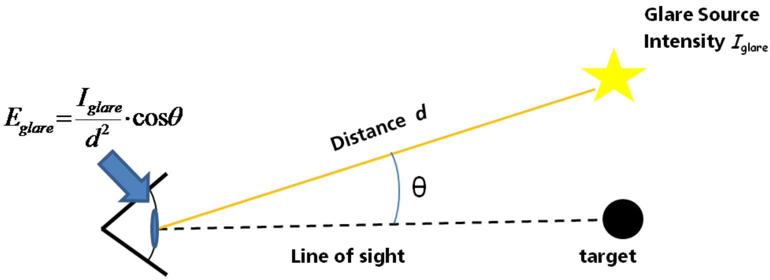


Figure 2–1: The illuminance at the eye caused by glare source according to CIE [23].

Disability glare usually happens at night time when the adaptation luminance is low and bright light sources are presently close to the line of sight e.g. what we experience during the night- driving when the headlight of the other car driving toward us is turned on. Although disability glare does not occur exclusively at night time and may also happen in daylight conditions with a bright light source like the sun close to the line of view.

2.3 Veiling glare

Veiling glare occurs when the reflection superimposes itself upon a visual target and causes difficulty in seeing the target. Due to the reflection, the luminance of the object to be seen is intensified by the extra luminance which results in reducing the contrast and hence the visibility of the object; this phenomenon is called veiling reflection or veiling glare. Veiling glare could be of a different significance level dependent on the different visual targets. This level is related to the required contrast for visibility of that target. For instance, in the case of the target being a reading or writing task, contrast is a more sensitive subject compared to a visual task such as watching a movie. Therefore the procedure of evaluation of veiling glare can be defined as:

1. Definition of the visual task
2. Determining the required luminance contrast for conducting the task
3. Estimation of reflection luminance superimposed upon the task
4. Evaluation of veiling reflection

2.3.1 Veiling glare on visual displays

According to the main topic of this research study the focus of this chapter is on the aspect of glare called veiling-glare while working with visual displays. The surrounding light sources or bright objects could reflect onto the screen surface and result in contrast reduction so that the contrast between the target (e.g. the exposed text) and its immediate background goes below the minimum necessary value or minimum required contrast. For understanding the phenomenon of veiling glare on visual displays it is essential to clarify the reflection characteristic of the visual displays and the concept of minimum required contrast.

2.3.1.1 Reflection and visual displays

Incident light on a surface might be reflected in the following three different reflection types depending on the optical characteristics of the surface (see Figure 2–2).

- Specular reflection: mirror-like reflection in one direction, without any scattering.
- Lambertian reflection: uniform scattering in all directions. The brightness of the surface will be identical from all view directions.
- Haze or spread reflection: diffuse reflection around the specular direction.

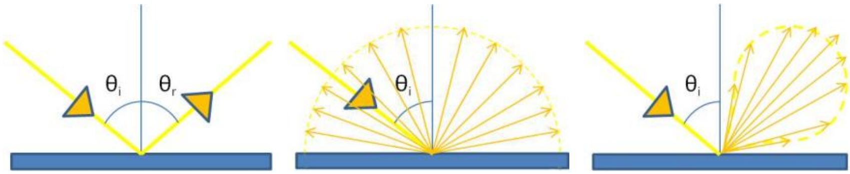


Figure 2–2: Left: specular reflection; Middle: Lambertian reflection; Right: haze or spread reflection.

In general there are three main types of visual displays that are used for the computer screens, in the following there is a short introduction to various visual-display types used as either a computer or a laptop screen:

Cathode Ray Tube or CRT: This is the oldest technology between visual-displays. CRT displays were the main visual-displays until the late 1990s, before being replaced by LCD technology. In CRT monitors, a vacuum tube containing a source of electrons, projects electron beams across the inside of the screen to illuminate phosphor dots in a series of many lines which create an entire screen-full image (i.e. a light emitting fluorescent screen). In respect to both size and weight the CRTs are the largest monitor types and have curved screen surface. CRTs have a subtle "flicker" in their display, which causes eyestrain. This display type cannot be applied in laptops. CRTs can be seen from a wide viewing angle and their manufacturing cost is significantly lower than other display units [71].

Plasma Display Panel or PDP: A plasma screen is an emissive display type which generates its own light. It is an array of millions of pixels positioned between two insulated electrodes and two glass panels and each pixel is basically a phosphor coated luminous cell or in other words a tiny fluorescent lamp (filled up with inert gases). The plasma cells are lit up through the row of a column array of electrodes situated in either side of the cells before the glass panels. Any pixel comprises three colors (red, green, blue) and can generate the whole spectrum of color. The plasma screens can create high resolution images with richer colors compared to LCDs and CRTs. The PDPs are often used in televisions and presentation displays with large screens but also in computer screens and can be seen from a very wide viewing angle. PDPs are usually more expensive than other visual display units [71, 55, 76].

Liquid Cristal Display or LCD: The first applications of LCDs were in devices like laptops and calculators. But from the late 1990s LCDs began to replace CRT monitors. In this technology each pixel comprises the liquid crystal molecules which are aligned between two electrodes and two crossed polarizers. The alignment of the molecules defines state of polarization i.e. whether the light passes through the pixel or not. LCDs are not emissive displays and often include a backlight as light source. LCD screen are flat panel screens. Comparing to CRTs, LCDs offer better image contrast and higher resolution, less energy consumption and less eye strain (as they don't flicker). Nonetheless they are more expensive and have a narrower viewing angle than CRT monitors.

According to Becker [6], the reflection characteristics of the above described visual displays are one of the following combinations of the three mentioned basic reflection types:

- **CRT**: combination of Lambertian and Specular but no haze component.
- **PDP**: combination of all three Lambertian, specular and haze components.
- **LCD**: combination of different amounts of spread and specular components but typically no Lambertian (or very low amount of Lambertian). The haze component is caused by applied scattering anti-glare treatment on the front surface of the display [7]. LCDs usually contain a minor amount of specular component unless they would be intentionally converted to mirror like surfaces due to commercial reasons.

To obtain the exact reflection property of any visual display, it is required to perform some measurements. The accuracy of the achieved reflection method would be very much dependent on the accuracy and complexity of the measurement methods. The display types such a LCDs which comprise the reflection component of haze require more advanced measurement methods. Becker states in his study that "neglecting the haze component in the evaluation of visual display reflectance often causes inconsistencies of the results" [7]. For measuring the haze reflection, some particular measurement methods are required. The respective measurement procedures in this regard are described in detail in chapter-7.

2.3.1.2 Existing models for minimum required contrast for monitors

To support a good legibility and visual performance, contrast ratio between the visual target and its background on the screen must exceed a minimum value. There are several studies dealing with the influence of contrast ratio on visual performance while working with visual display units. Wang and Chen investigated the effect of polarity and contrast ratio on visual performance and subjective estimation of display quality and concluded that the effect of contrast on visual performance and display comfort of the subjects was significant [73]. Lin also performed a study to investigate the effect of contrast ratio and text color on visual performance for TFT-LCD monitors and concluded that the contrast ratio significantly affects the visual performance, but text color did not influence the visual performance if an acceptable level of contrast ratio was present [44].

Contrast ratio of a displayed image is defined as the luminance of the brighter area divided by the luminance of the darker area:

$$CR = \frac{L_H}{L_L} \qquad (2\text{–}4)$$

L_H: high state luminance [cd/m²]
L_L: low state luminance [cd/m²]

By considering the value of reflection luminance on the image, this equation is formulated as the following [36]:

$$CR = \frac{L_H + L_r}{L_L + L_r} \qquad (2\text{–}5)$$

L_r: reflection luminance [cd/m²]

There are various suggestions and discussions about the minimum necessary value of contrast ratio for a good visual performance. In the next part some recommendation for minimum CR in various available international standards are reviewed. These standards are three publications of ISO (International

Organization for Standardization) issued in 1992, 2001 and 2008.

Model 1- ISO 9241-3:1992 [35]

According to this standard, the minimum contrast ratio within and between the characters and their background to provide legibility is:

$$CR_{\min} = 3:1 \tag{2–6}$$

This minimum contrast ratio has also been stated in other references. For example the ANSI/HFS 100-1988 also recommended that the contrast ratio should be greater than 3:1 [73 according to 1].

Model 2- ISO 13406-2:2001 [27]

As stated in this standard the contrast ratio of the displayed information on the computer screen must exceed the following minimum value to provide a good visual performance.

$$CR_{\min} = 1 + 10 \cdot L_L^{-0.55} \tag{2–7}$$

According to the performed literature review within current research, the underlying study for this model is unknown. Further investigations through the given references of ISO 13406-2 and via discussion with the respective contact persons could also not be of an aid in this regard.

Model 3- ISO 9241-303:2008 (Annex D) [36]

In the latest available standard concerning the minimum contrast for visual displays, a new model is proposed which is based on both older mentioned standard models and the contrast threshold model of Kokoschka [39]. The reason and procedure of proposing this model is described here, as stated in [36].

As visible in Figure 2–3 the both corresponding curves to both CR_{min} in previous standards cross at the point of L_L=18.7, below and above this value the predicted required contrast of the two ISO models is greatly different.

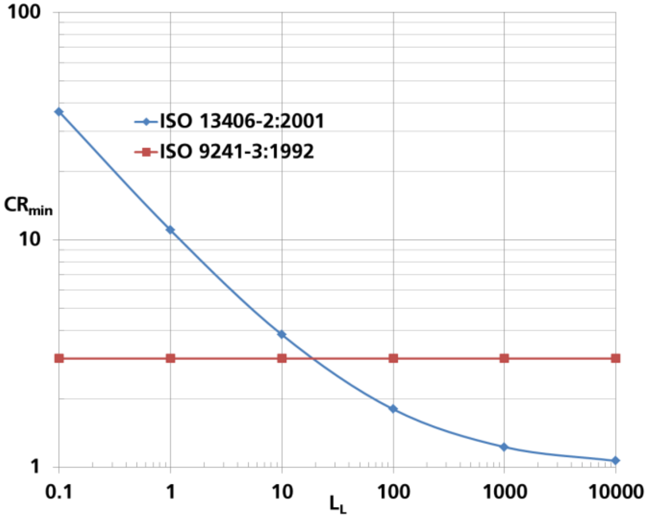


Figure 2–3: Corresponding curves of the minimum contrast in ISO 9241-3 and ISO 13406-2 (according to 36]).

In order to find a compromise and as another alternative, ISO 9241-303 proposed a third model for CR_{min} which is based on the mathematical evaluation of Kokoschka [36 according to 39] performed on the results achieved by Blackwell in the middle of the 20th century. The Blackwell study was conducted to assess the contrast threshold of a normal human eye and was based on visual detection tasks. The Blackwell study was carried out with young test persons and the task was the detection of a disk which appeared on a darker background with different visual sizes from 0.6 to 360 minutes of arc and various exposure times of up to 15 seconds [12]. It should be mentioned that the experimental conditions under which the Blackwell study was carried out is very different to the work on visual displays in office spaces. In this experiment, the observers were seated at the rear of the test room almost 18m away from the screen on which the stimulus (a spot of light in the shape of a disk), was projected and their task is to report whether they have seen the stimulus or not.

According to ISO 9241-303 the procedure of developing the new model for minimum contrast reads:

$$\overline{C} = \frac{L_H - L_L}{L_L} = f(L_L, \alpha)$$

$$\overline{C} = \overline{C}_{\min} \cdot f_1 \cdot f_2 \qquad (2–8)$$

$$\overline{C} = 0.00275 \cdot f_1 \cdot f_2$$

$\overline{C}$: contrast threshold

α: angular size of visual target [minute of arc]

And:

$$f_1 = 1 + \left(\frac{L_L}{0.158}\right)^{-0.484}$$

$$f_2 = 1 + \left(\frac{\alpha_0}{\alpha}\right)^2$$

$$\alpha_0 = 7.5 + 133 \cdot \left[1 - \frac{1}{1 + \left(\frac{L_L}{0.00075}\right)^{-0.383}}\right]$$

By converting the contrast threshold model to contrast ratio model the model becomes:

$$CR = \frac{L_H}{L_L} = 1 + \overline{C} \qquad (2–9)$$

Depending on the size of the visual target, the visual contrast threshold is adjusted by a constant value called k, to achieve the CR_{min}. Considering the mentioned common point ($CR=3$, $L_L=18.7$) in Figure 2–3 as starting point for developing the new model would provide a constant value for visual target of $\alpha=1'$:

$$\overline{C} = 0.321$$

$$CR = 1 + k \cdot 0.321 \qquad (2–10)$$

$$k \approx 6.3$$

In this standard the adjusted visual contrast threshold for a target size of $\alpha=1'$ is proposed as the minimum required contrast for visual displays:

$$CR_{\min} = 1 + 6.3 \cdot \overline{C}$$
$$CR_{\min} = 2.2 + 4.84 \cdot L_L^{-0.65} \quad (2\text{–}11)$$

The corresponding curve for this minimum contrast model is illustrated in Figure 2–4. This diagram affords the possibility of making a comparison between the last model and new proposed model.

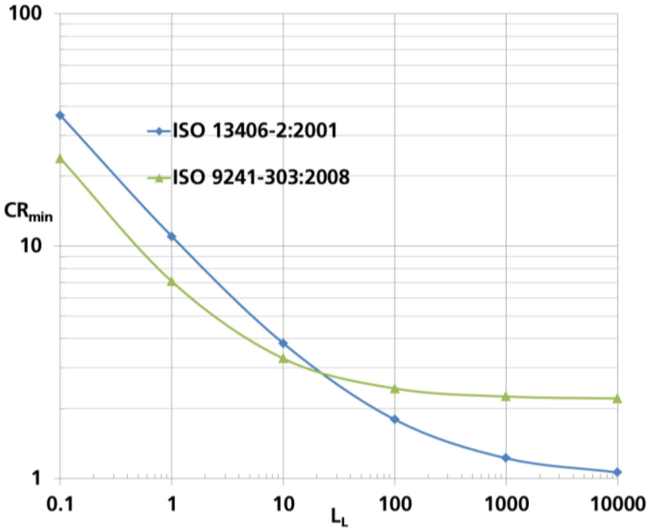


Figure 2–4: Corresponding curves of the minimum contrast in both ISO 13406-2 and ISO 9241-303 (according to [36]).

The basic data for the above-mentioned contrast requirement was attained by experiments on younger users.

Table 2-1 demonstrates the age multipliers (k_{age}) which are presented in ISO 9241-303 to be applied on CR_{min} for different ages. This table is originally proposed by Blackwell and Blackwell [14] in their study on threshold contrast with 156 observers from 23 to 68. The visual task in this study was the detection of 4-minutes luminous disk exposed for one-fifth second on an observation screen 0.91m away from the observers.

Table 2-1: Table of age multiplier proposed by Blackwell [14].

Age of users [years]	Contrast multiplier (K_{age})
20	1.00
25	1.00
30	1.02
35	1.07
40	1.17
45	1.34
50	1.58
55	1.90
60	2.28
65	2.66

This fact that visual performance could be affected by aging has been often discussed and studied. According to the literature, the following changes in the visual system occur by aging [66, 24]:

- Decreasing of the light transmittance of the eyes that results in the reduction of the light incident on the retina
- Yellowing of the eye lens
- Increasing of the light scattering in the ocular media
- Reduction in accommodation amplitude
- Decreasing of the functionality of the retina
- Reduction of the size of the pupil
- Decreasing of the amount of neurons responsible for visual information at the central part of the brain

According to above mentioned aging effects in the ocular media, the age should be taken into account as a potential factor by performing any study regarding visual performance and visual comfort.

In addition to the above mentioned standard models of contrast requirement for display-associated visual tasks, in the conducted literature review another contrast model came also into consideration. This model was proposed by Poynter in his study about the threshold contrast and English-letter/ image recognition [58, 59]. According to his model the amount of luminance contrast that is required to resolve the lettering and graphics is not constant and depends upon the image size, several photometric variables and observer's age and reads as follow:

$$TC_{non-std} = TC_{std} \cdot M_1 \cdot M_2 \cdot \ldots \cdot M_n \qquad (2\text{–}12)$$

$TC_{non\text{-}std}$: non standard threshold contrast
TC_{std}: standard threshold contrast
M_1 to M_n: contrast multiplier for background luminance, age etc.

The terminology of luminance contrast in this study is used for the following contrast index which is according to Weber contrast model:

$$contrast = \frac{L_{\max} - L_{\min}}{L_{\min}} \qquad (2\text{–}13)$$

The standard contrast threshold in Poynter's study is defined with the following equations:

If image size < 0.2°: $TC_{std} = 0.0728 + 0.0272 \cdot \frac{1}{size}$ (2–14)

If image size > 0.2°: $TC_{std} = (69.197 + 31.217 \cdot \ln(size))^{-1}$ (2–15)

Image size in these equations is the height of the letters in degrees and the task for deriving the above models has been the adjustment of the luminance contrast of the images (three English letters) upward (starting from 0) until at least two of them could be correctly recognized on a CRT display with a background luminance equal to 12cd/m^2. The proposed multiplier for other amounts of background luminance, M_{back}, in this study is a function which has been developed based on the Blackwell study in 1959 [13] and the proposed multiplier for age, M_{age}, is also another function developed based on the study performed by Blackwell and Blackwell in 1971 [14]. The equations to obtain these multipliers are as the following:

$$TC = (4.31295 - 0.01211 \cdot BK^3 + 0.02089 \cdot BK^2 + 1.2065 \cdot BK)^{-2} \qquad (2\text{–}16)$$

$$BK = \ln(BL)$$

BL: background luminance [cd/m^2]

$$M_{back} = \frac{TC_{BK}}{TC_{12}}$$

$$M_{age} = 1.95 + 0.00114 \cdot (age)^2 - 0.06511 \cdot (age) \qquad (2\text{–}17)$$

In addition to M_{age} and M_{back}, three other contrast multipliers have been considered in the Poynter study to be applied on the equation 2–12. A multiplier for color, M_{color}, has been considered to add up the effect of color contrast in addition to the luminance contrast to the model. A multiplier of veiling luminance or M_{glare} has been also defined to consider the effect of veiling luminance of the glare-source (present in the field of view) in the model. Furthermore, a multiplier of task variable has been defined in order to consider also a supra-threshold level of contrast beside the threshold contrast and has been obtained by asking the subjects to adjust the luminance contrast of display image to a comfortable and readable level; the average achieved value in the Poynter study for this multiplier is equal to 5.6 and the M_{color} and M_{glare} are defined with the following equations:

$$M_{color} = \frac{1}{1 + 3 \cdot |\Delta u'| + |\Delta v'|} \tag{2–18}$$

u' and v': dimension of 1976 UCS color space

$$M_{glare} = \frac{BL + L_v}{BL} \tag{2–19}$$

BL: background luminance of the display [cd/m^2]
L_v: veiling luminance over the retinal area [cd/m^2] which is equal to:

$$L_v = \frac{5 \cdot L_g \cdot \cos\beta \cdot \omega}{\beta} \tag{2–20}$$

L_g: luminance of glare source [cd/m^2]
β: angle between glare source and the line of sight [degree]
ω: size of glare source [sr]

Although the standard threshold contrast model (TC_{std}) available in the equations 2–14 and 2–15 has been developed via an experimental study using CRT monitor but as stated in the reference [59] the whole model is based largely on Blackwell studies which have not been visual display associated experiments.

2.3.2 Summary and discussion

Three different ISO standard models and another model developed by Poynter were described in this part which to the knowledge of the author, are the available models for a minimum required contrast on computer screens. The most recent model is ISO 9241-303 proposed at 2008 [36] which is a function of age and low state luminance of the displayed image. This model has been developed based on the results of the Blackwell study with a task of detection of the bright disks appeared on darker background [12, 38]. Furthermore, TC_{std} in Poynter model (equations 2–14 and 2–15) is based on an experiment with the task of recognition of white English letters on a darker background (on a color CRT) [58, 59]. This means that the underlying experiments for the existing models have been conducted with negative polarity (bright image on dark background), while most of the onscreen tasks in today's offices are performed with positive polarity (e.g. black text on white background). Moreover, in none of those models adaptation luminance of the observer's eye is taken into account. Though Poynter considers the effect of disability glare with a glare multiplier (M_{glare}) in his model, however, this effect represents the conditions when intense light sources are present in the peripheral visual field (*2.2-Disability glare*) and is different to the adaptation level of eye which is related to the ambient luminance in the visual field.

3 Experimental study to show the importance of veiling glare evaluation

3.1 Method

After performing a literature review about the concept of veiling glare on visual displays in the last chapter, this chapter deals with a preliminary study that explains how to estimate veiling glare on the monitors in a real office environment. This is an experimental study to compare the user estimation of visual displays with two factors i.e. window-luminance (suggested factor by standards) and a preliminary veiling glare factor. The purpose of this chapter is to test the hypothesis of this Ph.D. research in regards to which, veiling glare must be a relevant factor for evaluation of the visual quality of visual displays in office spaces.

The dataset used for this chapter has been adopted from a former user assessment study which was conducted to evaluate visual comfort in office spaces. This experimental study was a European project “Energy and Comfort Control for Building management systems” (ECCO-Build, Contract N°: ENK6-CT-2002-00656) which was launched in 2002 and ended in 2006. Project partners were SBI (DK), Servodan AS (DK), Ingelux(F), EPFL (CH), Hüppelux (D), Bug Alu Technik AG (AU), Technoteam (D) and Fraunhofer ISE (D) [18].

3.1.1 Project methodology

The images and observational data to be applied in this chapter are from the above mentioned project conducted at the Fraunhofer ISE. The project description in the following was not defined or designed for the purpose or in the framework of this Ph.D. research. This experimental project was developed and performed in order to study visual comfort in office spaces and was already finished when the current part started [82, 83]. For the purpose of the current evaluations the relevant datasets from this project are selected and applied in this part of research.

This user assessment study has been conducted in a daylight laboratory with two office-like test rooms located in the southwestern part of Germany in Freiburg on the roof of the main building of the Fraunhofer ISE. These rooms are completely rotatable and are identical in photometrical (ρ_{wall} = 0.56, $\rho_{ceiling}$ = 0.80, ρ_{floor} =0.34) and geometrical attitude (3.65 m wide, 4.6 m deep, 3.0 m high). The glazing area of the both rooms are from sun protective double-glass with a light transmission of $\tau_{\perp}$ = 54%, a U-value of 1.1 W/m^{2}k, and a total solar energy transmission of 29% 83].

One experiment room was used for user assessments (test room) and the other one was equipped with measuring instruments (reference room) (see Figure 3–1). All necessary measurement equipments were located in a reference room which has the same visual environment as the test room. This provided the possibility of locating a luminance camera at the same position as the subject's eyes in the other room to capture the fisheye pictures from the entire field of view. Both rooms were equipped with a desk, an office chair and a computer. The workplace was next to the window and subjects were seated 1.5 m away from the window. The used visual display was a flat panel display model, Eizo FlexScan L565 (max. self-luminance 190 cd/m²) [83].

The subjects were exposed to three different window sizes typical for offices. The window adjustment could be easily changed from a fully glazed facade to a partially occluded one (small and medium sized windows). These three different window sizes included a small punched window (sill-height at work plane), a medium sized seamless window (same height as the small window) and a large size fully window façade (see Figure 3–2). In this study three shading systems were applied as the following:

- White venetian blinds, 80mm convex
- Specular venetian blinds, 80mm concave
- Vertical transparent foil

Figure 3–1: Images of test room (left) and reference room (right).

Figure 3–2: Images of the test rooms with the three window sizes (left - small size window, middle- medium size window, right – large size window) [83].

The tested viewing directions for different shading devices were as the following:

- White venetian blinds
  - viewing direction parallel to window
  - viewing direction diagonally toward window (45°)
- Specular venetian blinds & Vertical foil
  - viewing direction diagonally toward window (45°)

Each subject had to perform a pre-test and three successive test phases according to three window adjustments. Each phase included four parts:

- Reading test
- Typing test
- Letter search task
- Adjustment of shading device

Pre-Test

In this phase the subjects became familiar with the whole process by performing short samples of "typing" and "letter searching " tasks and filling out exemplar questionnaires.

Reading Task

Reading task was a paper based task. The subjects had to read a simple text taken from newspaper in a limited time period (4 minutes).

Typing Task

The typing test was performed on the computer screen and consisted of retyping a given text into a defined window for this purpose (see Figure 3–3). The users were required to type correctly and correct mistakes in order to go further with typing. Typing speed and errors were recorded and applied later to compute the subjective performance measure.

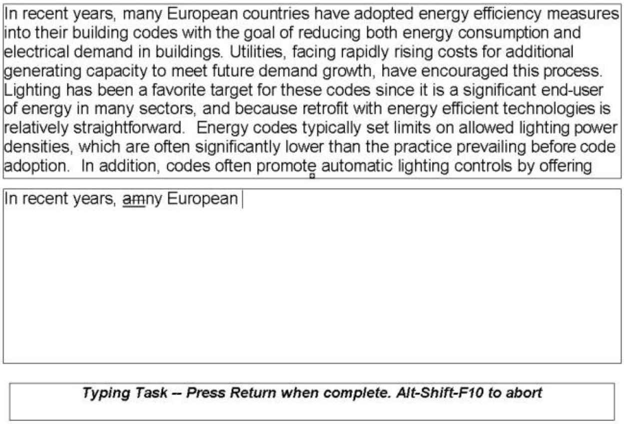


Figure 3–3: An example of the Typing Task developed by National Research Council of Canada NR, which measures the speed and accuracy with which the subject is able to retype a given text [83].

Letter Search Task

This part included a pseudo-text which was a block of characters which appeared on five locations on the screen (upper left, upper right, lower left, lower right and centre). The task was to scan the text and to find a defined target character (for example letter A) and to count the occurrence times (see Figure 3–4)

```
WhwNdzo zltpVY 1CCAe kDw he t3
TkW3rm8U ya BpE O2B L8Y A5 She
PQtb 90DViRCDG 1H pSM yEqZz 6F
jyA3 sATQesa ANUU VLH Ou1p2JBE
vbR l1Y5rVr SA9mr DmPETLV 2uO2
7phnFd2oyT 83ee zKo8h KyiTJgAL
vXMu 6Kugm 3ElkxsOWhCK1FTMA T6
LuGF5 ad HsicT H0jkHv ssAq U8Q
8dW rmrtfGqh HCsnGdYIMQEITS fo
o1 XVw6 2VogMFo6 PH uJD3c DXj8
yW 5LN 6Bv0 fGPhdZ Cn x9gUiaH3
fySFoauaxj UeK bKQz 2uZa MmnCN
4t HT3OFuMUSo piq1uUh8tdRbK1Tn
Ez 33Q 6w fvVR 7B gyz Ns5 5Ami
7T5k 6bc2 ZHl fJmDO GwJ9 ECKYm
Xob3m t9 SU ZR e1 3lFg 1wc j4w
nToPDF RCUb nyMHs rMI0oizFL8dx
a2Z sD AK5R1 Q8jiI wBeeA L2Rz0
```

Figure 3–4: An example of a pseudo-text [83].

After each part the subjects had to fill out respective questionnaires to point out their estimation about the task, lighting and comfort. In the following there are short explanations about the mentioned parts, for further detail on these tasks refer to 83].

Measurements

- **Luminance distribution within the view field**

A CCD camera from TechnoTeam (LMK 98-2 Luminance Video Photometer) was used to measure the luminance distribution within the subject's field of view. This calibrated, scientific-grade CCD camera was mounted on a tripod located in the reference room, at the same position as the observer's eye in the test room. The camera was arranged to automatically take fisheye pictures from the entire view field every 30 seconds during the whole experiment.

- **Indoor illuminance values**

Illuminance values were measured every 10 seconds by means of Lux-meters at different places in the reference room such as:

  - One sensor on the same tripod together with the CCD camera to measure illuminance at eye level.
  - One sensor on the corner of the monitor directed toward user person, in both rooms.
  - Five sensors on the work plane, 85cm from the floor in the reference room and one sensor in an identical position in the test room.

The order of the whole procedure for each subject is summarized in Table 3-1, which is adopted from the PhD study described in [83].

Table 3-1: Order of test procedure [83].

Start of experiment	Short Introduction General Questions Pre-Test
Phase I (1st window configuration)	Reading Task I Questions about Reading Task I Typing Task I Questions about Typing Task Letter Search Task I Questions about Letter Search Task Questions about light situation in room Adjusting of shading devices by the subject Questions about reasons for changing
Phase II (2nd window configuration)	Reading Task II Questions about Reading Task I Typing Task II Questions about Typing Task Letter Search Task II Questions about Letter Search Task Questions about light situation in room Adjusting of shading devices by the subject Questions about reasons for changing
Phase III (3rd window configuration)	Reading Task III Questions about Reading Task I Typing Task III Questions about Typing Task Letter Search Task III Questions about Letter Search Task Questions about light situation in room Adjusting of shading devices by the subject Questions about reasons for changing
End of experiment	Questions on indoor climate conditions

3.1.2 Experimental procedure

The given information in the part of *3.1.1- Project methodology*" is in fact a report of a completed project which was conducted outside of the framework of this Ph.D. Some results of this project are selected and used for the purpose of intended evaluation in this chapter. Thereafter the explanations are about the current evaluations within this research study based on the adopted results from the finished project. Since the mentioned project was implemented under daylight conditions, the subjects might have often been confronted with reflection associated contrast deficiency on their screens while performing on-screen visual tasks. The purpose of this chapter is to study the relationship between the user estimation of screen visibility and the reflection related veiling glare on the screens. For this reason the following requirements shall be provided by the available project-results:

- Information about reflection on the screen-> from luminance pictures
- Subjective estimation of screen quality-> from questionnaires

First step is to select an appropriate part from the available dataset to perform the intended evaluation.

3.1.2.1 Data selection

The dataset selection process includes the following parts:

- Selection of the suitable luminance distribution pictures for deriving the reflection luminance on the screen.
- Selection of the respective screen-based task which time wise would be close to the selected pictures.
- Selection of the appropriate subjective responses regarding screen quality in the questionnaires.

First it is necessary to select the appropriate luminance pictures, to derive the luminance due to reflection on the screen, from all fisheye pictures which have been taken every 30 seconds during the experiments. For calculation of reflection luminance on the screen, the pictures with a homogenous screen are required (i.e. the screen had either totally black or completely white background). Therefore it is decided to select the images which were taken during the reading task. The reading task was a paper-based task and during which a screen-saver status was active on the monitor with a homogeneous black background.

Next step is to choose a task which has been both screen-based and timely close to the selected pictures. As visible in Table 3-1, the first screen-based task after reading was the typing task. The time difference between when there is a black screen and when user starts to type is less than one minute. So, the reflection level on the monitor could not have been considerably changed. But to provide certainty, the vertical illuminances measured on the corner of the monitor during both the typing and reading phases are compared and the cases with more than 20% difference are omitted and not considered in the evaluation process. Between all questions regarding visual comfort and lighting condition in the questionnaires, there is a question which is more relevant for the purpose of this study and is therefore especially considered for current evaluation. This question reads as “When typing the text, where you bothered by reflections on the screen?” The response to this question is in the shape of a line rating scale, from “not at all” to “very much” (see Appendix A)

3.1.2.2 Image processing to derive reflection on screen

As mentioned before, the available images for this study are fisheye pictures captured from the view point of the user looking at the computer screen. As visible in Figure 3–5, the computer screen in these images is distorted due to the fisheye lens effect. For computing the reflection luminance on the screen the next three steps shall be performed:

a. Deriving the luminance of the black screen-saver in available images captured under daylight conditions

The first step is to process the fisheye images to derive the luminance of the monitor. A computer based tool has been developed for this reason which affords the following procedure (see Figure 3–5):

- Detection of the monitor screen in the whole images
- Cut and reform the distorted monitor to rectangular shape

Input to the developed tool is a RADIANCE picture format (*.pic) with a fisheye field of view. The relevant captured images by CCD camera are converted to RADIANCE picture files for this reason. The output of the tool is also a RADIANCE picture file containing the reformed and cut screen area. By means of RADIANCE routines, the cut screen images are resized to the original resolution of the monitor equal to 1280px*1024px and the luminance of all monitor-pixels are computed and saved in the respective files. These files include the luminance information of the screen considering daylight-related reflection.

b. Deriving the luminance of the black screen-saver under dark room condition

To achieve the magnitude of reflection luminance on the computer screen in the images, it is necessary to have the value of initial screen luminance without any reflection. The following procedure is performed to derive the initial luminance:

- The monitor with black screen-saver in a totally dark room is photographed by the CCD camera with the fisheye lens from the same view point as of the available images (see Figure 3–5, left).
- The captured image is converted to RADIANCE format and is processed by the developed tool to cut and reform the screen.
- By using RADIANCE the cut screen is resized to 1280px X 1024px and the luminance values of all pixels are computed and saved in a reference luminance file.

By subtracting the luminance values after and before reflection, the values of reflection luminance for all cases are computed.

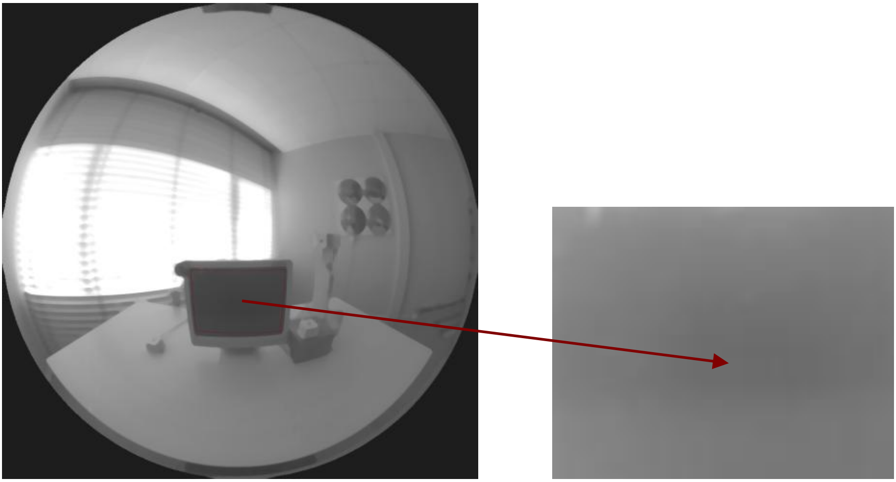


Figure 3–5: Left: fisheye pictures captured by CCD camera are converted to RADIANCE format to be processed by developed tool.
Right: cut and reformed monitor screen by means of the developed tool is saved in a RADIANCE picture to derive screen luminance after reflection.

3.1.2.3 Contrast study

After deriving the reflection luminances in all cases using the available pictures, the next step is designing a proper method to implement contrast evaluation. To start with, the initial contrast ratio without reflection effect is determined. As previously mentioned, the underlying task of this study was a typing task with black text on the white background. Therefore the initial contrast ratio would be the contrast of black letter and white background.

$$CR = \frac{L_{white}}{L_{black}} \qquad (3\text{–}1)$$

L_{white}: luminance of white background [cd/m^2]
L_{black}: luminance of black text [cd/m^2]

To obtain the initial luminance values of the background and text some reference luminance pictures in a totally dark situation shall be taken and processed according to the following steps:

- Setting the monitor with a completely white background (the same background as typing task) and taking picture by CCD camera (see Figure 3–6).

- Measurement of the luminance of the black text is not as easy as measurement of white background. Whether the luminance of a black text is equal to the luminance of a black screen saver or not should be investigated. For this reason the next procedures are conducted[2]:
    - Exposure of a black letter on the screen
    - preparing a black paper template containing very small cut square areas and positioning it on the monitor so that the cut spot could be located over the letter
    - measuring the luminance of the black letter behind the spot by means of a spot luminance meter (the spot area was almost 4 pixels)
    - Measuring the luminance of the black screen-saver at the same location of the monitor.

This process shows that a black screen saver and a black text have similar luminance and the luminance of the black text can be considered equal to the black screen-saver measured in a dark room. To facilitate the contrast evaluation, a pattern is required which should be a composition of both black and white luminance. The selected combination in this study is a grid of alternative black and white pixels. This arrangement delivers a chess shape pattern illustrated in Figure 3–7.

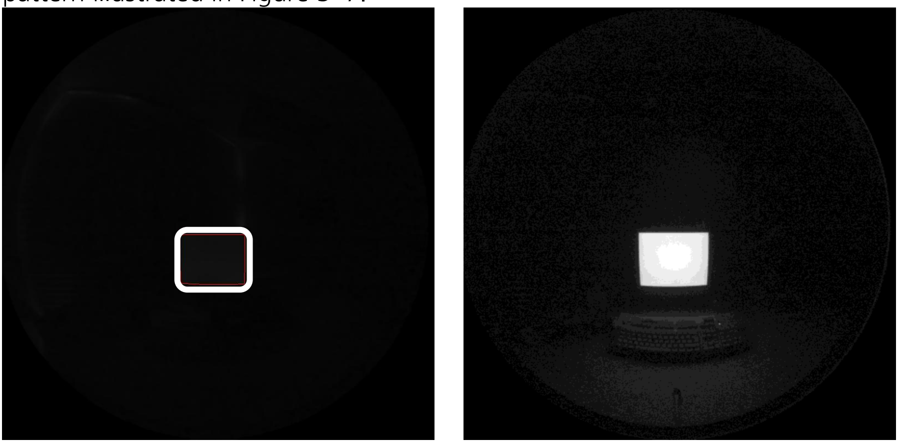


Figure 3–6: Left: luminance picture taken from a monitor with a black screen saver (which is equal to black text luminance) in a totally dark room [50].
Right: luminance picture taken from monitor with white background in a totally dark room [50].

[2] Measuring the luminance of black text on a bright background by means of CCD camera or spot luminance meter might have uncertainty due to the measurement error. This error may occur because of the effect of the bright surrounding on the dark area. Therefore the measured luminance value of the black text by this method might be much higher value than the real value.

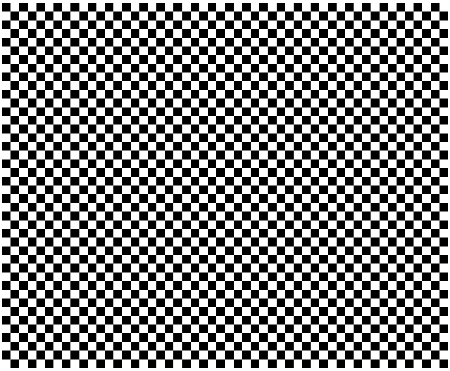


Figure 3–7: Black-white chess shape outline prepared from the reference images to be used as a reference pattern for a contrast study [50].

The reflection luminance values are mapped on the reference pattern and the contrasts between any two adjacent pixels are calculated as the following:

$$CR = \frac{L_{white} + L_r}{L_{black} + L_r} \qquad (3\text{–}2)$$

L_r: Reflection luminance [cd/m²]

3.1.2.4 Contrast deficiency classification

By conducting any visual task, contrast deficiency is defined where the contrast ratio between dark and bright area of the task becomes lower than the required contrast for performing the task. The required contrast for working with a computer screen in this chapter is based on the most recent standard model [36] (see equation 2–11). If this contrast model is a reliable basis or not, is out of the scope of this part and will be evaluated in the next chapter.

The value of contrast deficiency in this study is defined as the difference between the actual task-contrast (CR) and required contrast based on standard model (CR_{min}). This value is computed wherever the task-contrast is lower than the required contrast ($CR < CR_{min}$):

$$CD = CR_{\min} - CR \qquad (3\text{–}3)$$

CD: contrast deficiency
CRmin: required contrast based on standard model which is a function of a Low state luminance LL (equation 2–11)
CR: actual contrast based on standard model (equation 3–2)

For example if L_{white}= 150cd/m^2, L_{black}=1cd/m^2 and L_r= 200cd/m^2 we will have:

$$\left.\begin{array}{l} CR = \dfrac{150+200}{1+200} = 1.74 \\ CR_{\min} = 2.2 + 4.84(200+1)^{-0.65} = 2.35 \end{array}\right\} \quad \begin{array}{l} CR < CR_{\min} \\ CD = 2.35 - 1.74 = 0.61 \end{array}$$

In this research study a pixel by pixel contrast evaluation is performed for the whole screen area according to the next steps:

- Computing contrast ratio, required contrast and contrast deficiency between all neighboring pixels throughout the whole screen area using equation 3–3.
- Classification of the computed contrast deficiency values to different levels in order to facilitate a comparative study. The maximum computed contrast deficiency in all of the cases is equal to 1.5. Therefore between a minimum of 0 (no contrast deficiency) and the value of 1.5 (the maximum deficiency obtained in this study), a classification is conducted to categorize all the contrast deficiencies in three magnitude levels as the following:

$$\begin{array}{l} CD_1 : 0 < CD \leq 0.5 \\ CD_2 : 0.5 < CD \leq 1 \\ CD_3 : 1 < CD \leq 1.5 \end{array} \qquad (3\text{–}4)$$

- Determining the fractions of each screen which are confronted with contrast deficiency levels of CD_1, CD_2 and CD_3 (For example 2% of screen has CD_1, 10% has CD_1 and 5% has CD_3)
- Defining a preliminary Veiling Factor (VF) based on contrast deficiency levels. In order to simplify the evaluations a unique factor is required which represents the extent of veiling glare on each screen. This factor is considered as a linear function of all contrast deficiency levels:

$$VF = a \cdot F_1 + b \cdot F_2 + c \cdot F_3 \qquad (3\text{–}5)$$

VF: veiling factor
F1: screen fraction with contrast deficiency level 1(CD1)
F2: screen fraction with contrast deficiency level 2(CD2)
F3: screen fraction with contrast deficiency level 3(CD3)

It is necessary to make some assumptions for completing this factor. This is not a final method and the purpose is just to create a factor in order to make a comparison between all of the cases. Hence, the made assumptions are preliminary and not optimal. However, they are enough for the purpose of this study. Assuming:

$$If \begin{pmatrix} F_1 = 0 \\ F_2 = 0 \\ F_3 = 100 \end{pmatrix} \Rightarrow VF = 100$$

$$If \begin{pmatrix} F_1 = 0 \\ F_2 = 100 \\ F_3 = 0 \end{pmatrix} \Rightarrow VF = 90$$

$$If \begin{pmatrix} F_1 = 100 \\ F_2 = 0 \\ F_3 = 0 \end{pmatrix} \Rightarrow VF = 80$$

The veiling factor can be formulated as:

$$VF = 0.8 \cdot F_1 + 0.9 \cdot F_2 + F_3 \tag{3–6}$$

3.2 Results

Veiling factors are calculated for all screen images using equation 3–6 and according to the procedure explained in the part "*3.1.2.4. Contrast deficiency classification*". Afterwards some statistical evaluation is carried out between the calculated veiling factors and user assessments.

Figure 3–9 shows the relationship between the calculated veiling factor and user ratings of being bothered by the reflection on the screen. This is a box-plot presentation of the data in which the boxes correspond to the 50% of the observational data within the relevant group and the horizontal lines above and below the boxes represent the limit of the entire values.

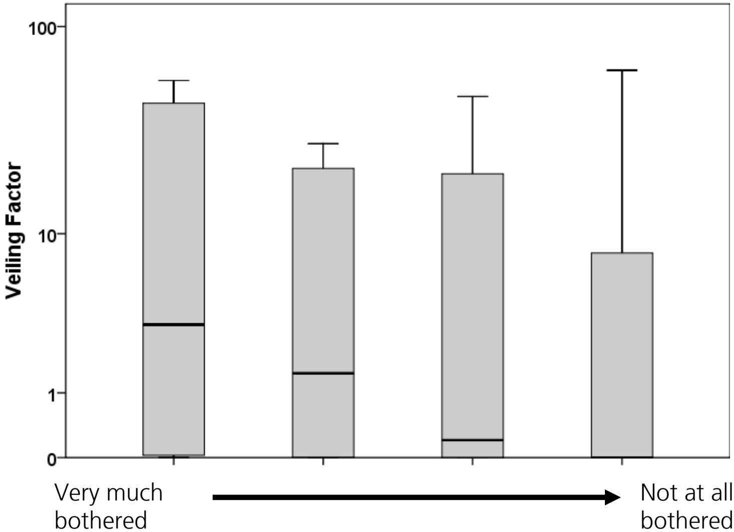


Figure 3–8: Box-plot presentation of "bothered by reflection on monitor screen". The boxes correspond to the 50% of the observational data within the relevant group and the horizontal lines above and below the boxes represent the limit of the entire values [50].

As visible in Figure 3–8, the agreement between the achieved VF and the subjective estimations is not very high but promising according to the median lines of the boxplots.

According to the standards [72] the luminance of the window's façade can be an indicator of the visual quality of the visual display in office spaces. Based on this standard the window luminance is recommended to be between 2000 and 4000cd/m^2 for working on visual displays if the windows do not reflect directly on to the screen (the existing conditions in this study).

The statistical analysis performed between the subjective ratings about visual quality of the screen and the luminance of the window shows that despite the standards, the luminance of the windows cannot be used for predicting the reflection related user's satisfaction of the computer screens (see Figure 3–9).

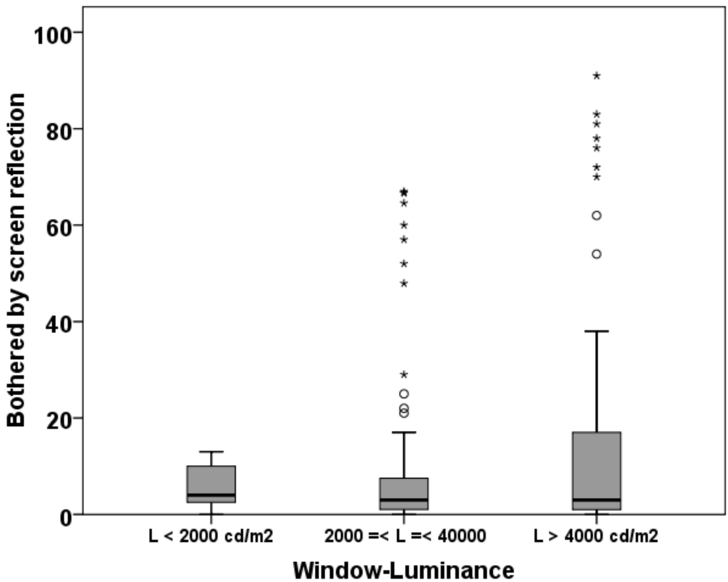


Figure 3–9: Box-plot presentation of the relationship between subjective estimation of "bothered by screen reflection" and "window luminance". The boxes correspond to the 50% of observational data within the relevant group and the horizontal lines above and below the boxes represent the limit of the entire values apart from outliers which are illustrated as extra points [50].

Table 3-2 shows the results of a statistical analysis performed based on a generalized linear model (GLM) to evaluate the relationship between the subjective rating of "bothered by screen reflection" as a dependent variable and the factors of "veiling factor", "window luminance" and "vertical illuminance at screen corner" (other hypothetical factor that might have relationship with visual quality of computer screens). The GLM model is selected for this evaluation because it allows us to include the subjects as fix factors and therefore enables us to consider the individual differences.

As visible in Table 3-2, there is a significant relationship between the subjective rating of "bothered by screen reflection" and the calculated "veiling factor" with a significance factor of 0.015 (values less that 0.05 are indicator of a significant relationship). But there is no relation between the subjective results and both factors of "window luminance" and vertical illuminance at screen corner".

Table 3-2: Results of the GLM evaluation; Dependent Variable: Bothered by screen reflection [50].

	F value	Significance	Number of observations
Veiling Factor	6.109	0.015	194
Vertical Illuminance at screen corner	0.001	0.978	194
Window luminance	0.483	0.488	194

3.3 Discussion

The comparison between both box-plot presentations in Figure 3–8 and Figure 3–9 and also the results of the GLM evaluation in Table 3-3, demonstrate that the new proposed veiling factor, VF, is a relevant indicator for estimating the visual display quality in office spaces. Despite its restrictions, the new factor matches the observational data, while the other two factors of "window luminance" and "illuminance at screen corner" do not show any significant relationship to the observations.

Hence, according to the current subjective study and despite standards, window luminance could not be used for estimating the reflection related visual satisfaction of the computer screens; also the value of light reached on the screen is not appropriate for predicting the screen quality. This shows the absence of a good principle for the evaluation of visual display quality. The attained agreement between the defined veiling factor and subjective ratings is a good base for further investigation in this regard.

Although the correlation between "bothered by screen reflection" and "veiling factor" is adequate in this stage and for the purpose of this chapter, it can potentially be improved due to the following reasons:

- Computed veiling factors are based on contrast deficiency due to both reflection aspects i.e. specular and diffuse reflection. But users were asked to rate their perception about specular reflection (German word:"Spiegelung") on the monitor.
- The contrast model used for this study should be validated or be improved for on-screen visual tasks (Chapter-5). This could lead to more accurate veiling reflection prediction and an improvement of the correlation results.

- The model used for calculating the veiling factor stated in equation 3–6 is based on primary assumptions and might not be an optimal model.

According to subjective results the conclusions of this chapter can be summarized in the following points:

- The new proposed veiling factor based on standard contrast model is promising for estimation of visual quality of computer screens in office rooms (This agreement could be potentially improved especially by improving the contrast model).
- Despite the standards [72], the luminance of the glazing area cannot be used for estimating the reflection related visual satisfaction of computer screens (it does not fit the observed data).
- Light level reached on the monitor (illuminance measured at screen corner) is not a good criterion for estimating the visual quality of computer screens (it does not fit observed data).

4 Experimental study to evaluate existing contrast threshold

4.1 Method

After concluding that the veiling glare method is a reliable method to evaluate the visual quality of computer screens in office rooms in the last chapter, the second step is to test the reliability of a standard contrast model as a basis for contrast evaluation on a visual display. This chapter explains an experimental user assessment in order to study the contrast perception of the trial persons by performing on-screen visual tasks.

The user assessment study described in this chapter is part of a broader research project mentioned in the part *"1.4- Background of the Thesis"* abbreviated with the name of "QUANTA". The purpose of the whole project is the evaluation of different factors such as age, brightness, outlook and color on visual comfort under daylight conditions in office spaces. This project is performed in a daylight laboratory located on the roof of the main building of the Fraunhofer Institute ISE containing two identical rotatable test rooms. The more detailed descriptions about this laboratory are achievable from the *"3.1.1- Project methodology"* in chapter-3. The main difference between the testing conditions in the current experiment and the one mentioned in chapter-3 is that within QUANTA both rooms are used for testing procedure. This means that two trial persons can simultaneously be tested in two test rooms and the users can exchange rooms during each trial. Depending on the focus points of the test-series i.e. brightness, color etc. this exchange would afford the possibility of testing more parameters in one trial.

4.1.1 Project methodology

QUANTA is a user assessment study within which each test person performs different tasks, such as contrast test, typing, searching etc. and fills out respective questionnaires in between the tasks to point out their estimation about lighting condition as well as their comfort level. Roller blinds and venetian blinds are used as shading systems in this study, and can be adjusted by the trial persons after having completed the first part of the test. In both rooms different types of venetian blinds and roller blinds are mounted to make the possibility of studying various shading systems.

By means of a CCD camera mounted on a tripod and located close to the head of the subjects, during the test period, luminance distribution pictures are taken automatically every 30 seconds from the whole field of view (using calibrated fisheye lens). The illuminance values are measured every 10 seconds at different places in the room e.g. on the workplace, at the screen corner and close to the position of the subject's eye. The tests are conducted in different series with various focal points with regards to outlook, brightness, age and color rendering index as potential factors affecting visual comfort. The entire process of the experimental study can be described in the following steps:

Phase 0: Short Introduction to test procedure

- **Questions:** about the person
- **Contrast test**
- **Typing task:** a short version of typing task on the screen
- **Performance test**: a short version of d2 test on the paper

Phase 1: under artificial lighting conditions without daylight; windows are covered with thick curtains

- **Contrast test**
- **Typing task:** on the screen: the task is to type a given text in a window without any mistakes (see Figure 4–1)
- **Questions:** about lighting situation during typing task
- **Performance test:** paper based d2 test, the task is to mark out all "d" letters with two bars between a bunches of "p" and "d" letters with one, two, three bars or four (see Figure 4–2)
- **Questions:** about lighting situation during d2 test and general lighting situation inside the room

Phase 2: under daylight conditions

- **Contrast test**
- **Typing task:** on the screen
- **Questions:** about lighting situation during typing task
- **Performance test:** paper based d2 test
- **Questions:** about lighting situation during d2 test and general lighting situation inside the room
- **Adjustment of the shading systems by subjects**
- **Questions:** about the reason for changing the adjustment of shading devices
- **Contrast test**
- **Typing task:** on the screen
- **Questions:** about lighting situation during the typing test and the general lighting situation inside the room

During each experimental trial different parameters are to be varied e.g.

shading systems or brightness or color rendering index or a combination of them. Phase 2 shall be repeated for each variant which results in up to four replications of phase 2 in most of the trials. The whole testing procedure takes about 1.5 to 2 hours. The described experimental procedure can be summarized in Table 4-1.

Table 4-1: The procedure of the entire experimental study in QUANTA.

Phase 0 (introduction)	Questions about person
	Contrast test
	Typing task (short version)
	Performance test (short version)
Phase 1 (under artificial lighting condition)	Contrast test
	Typing Task
	Questions
	Performance test (d2 test on the paper)
	Questions
Phase 2 (under daylight condition)	Contrast test
	Typing Task
	Questions
	Performance test (d2 test on the paper)
	Questions
	Adjusting of shading devices (by the subject)
	Questions
	Contrast test
	Typing task (on the screen)
	Questions

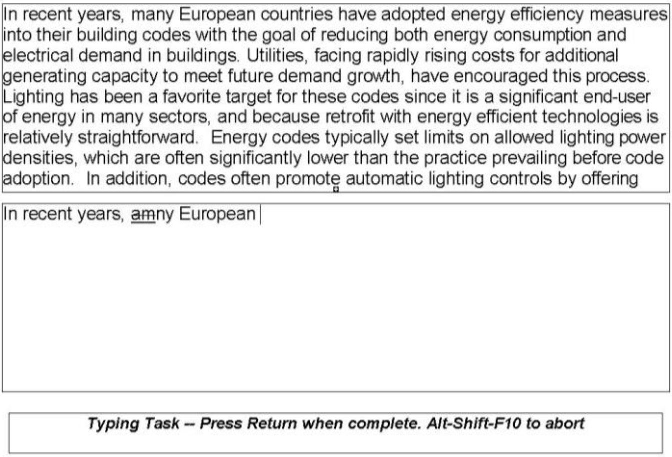


Figure 4–1: An example of the typing test. The subject is required to retype the given text in the bellow window correctly, in case of having mistake the curser would not go further until the subject corrects the word.

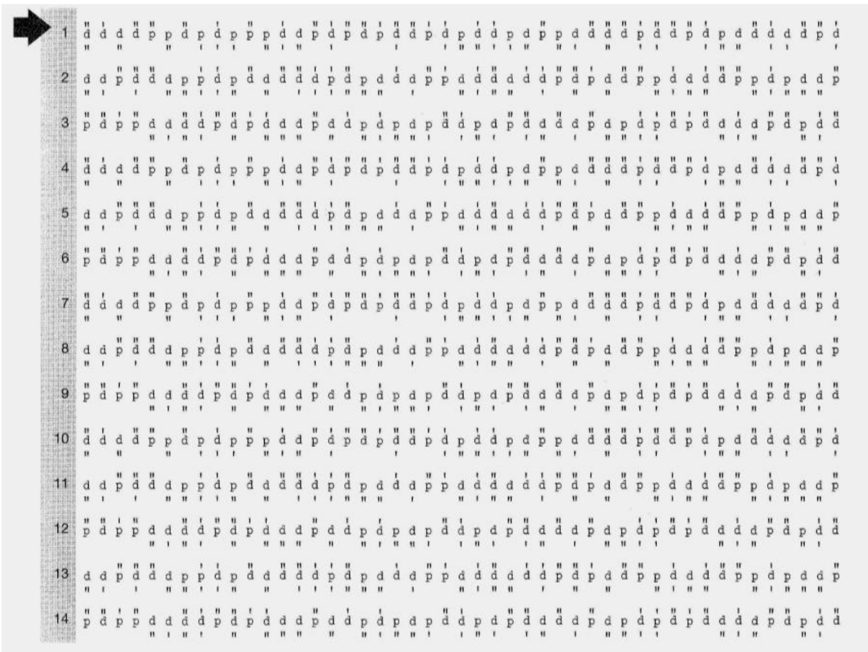


Figure 4–2: An example of a performance test; the task is to mark out the letters of “d” which have two bars without considering the positions of the bars relative to “d” (below, over or both).

The whole experimental study is implemented in the following series:

- **View-contact related series**: in this series the subjects are tested with two different outlooks from the window i.e. once with nice nature scenery and once with an industrial view.
- **Brightness related series**: in this run the subjects perform the test under four various brightness sets. The brightness is changed by applying natural-colored foils on the glazing area to reduce the transmittance of the glazing.
- **Age related series:** in the other test series the subjects are in the age range of 20-30 years. To evaluate the effect of the age on visual comfort, in this run two additional age groups are also tested. Additional age groups are 50-60 and age group of 60-70.
- **Color related series**: in this run, the spectrum of the incoming light from the window is varied by applying different colored foils on the glass façades. Three colored foils in bronze, green and blue are applied for this reason, which together with the natural-colored window glass constitute four variants to be tested in this series.

More details about the whole research study can be attained from the publications stated in [52, 53 and 54].

The contrast test is the part of this experimental project which has been designed for the purpose of this Ph.D. and is described in this chapter. The contrast test has been designed to study the contrast perception of the test persons while working with visual displays. The luminance distribution pictures are also taken from a position close to the eye position of the subjects in order to measure the reflection luminance on the screen. The user assessments of visual comfort before and after performing the tests are also asked via respective questionnaires.

In this research, the subjective contrast perception results that consider the luminance reflection on the screen are compared to the respective standard contrast model. The main purpose of this part is to assess how good the existing contrast threshold model can predict the observed contrast perceptions by trial persons.

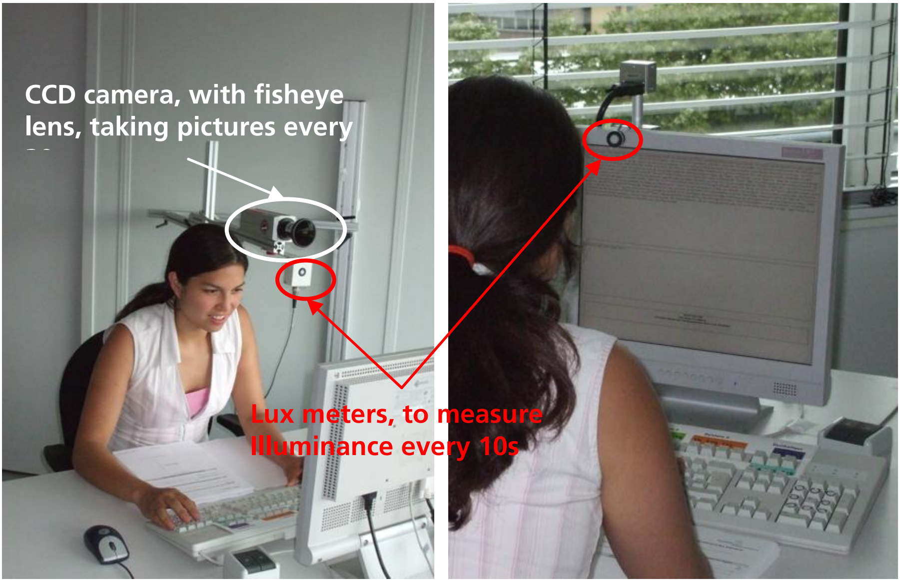


Figure 4–3: Images showing the test person by performing the test [54]. The CCD camera mounted on a tripod and positioned close to the subject's eye takes luminance pictures from the field of view every 30 seconds. The illuminance values close to the eye position and on the monitor corner and on the workplace are measured every 10 seconds using respective lux meters.

4.1.2 Experimental Procedure

4.1.2.1 Test description

The developed contrast test is based on a standard Landolt C test which is also used for ophthalmologic examination. Landolt C which is also called Landolt ring or Landolt broken ring, is an optotype, i.e. a standardized symbol which is used for vision testing. In this test the task is identification of the gap (broken opening) in the Landolt C. The considered visual size for the gap of the Landolt ring is about 3 minutes of arc. Each contrast test includes 30 different Landolt ring exposures, which occur one after the other on the computer screen. Each Landolt ring appears randomly on one of the five possible locations on the screen, with an exposure time of about 5 seconds (see Figure 4–4, right). The gap of the ring can be in eight different locations (see Figure 4–4, left). Before exposing of each Landolt ring a black cross-sign appears on the exposure-position to notify the users where to look. The searching time is excluded from the evaluation and the focus is just on the identification time.

The background luminance of the screen is fixed during the test and is set to a value of about 45-60 cd/m^2. The difference is due to the inhomogeneity of the LCD monitor. The foreground luminance (luminance of Landolt ring) changes randomly, but is always darker than the background. The order of exposures of the rings on the monitor and the orientation of the gap in each exposure and the luminance of each Landolt ring are all determined randomly by the respective programming method used for this reason. Altogether 100 different contrast tests are generated by the mentioned method and saved on the system; during the test procedure each time the start key of the contrast test is pressed one of the 100 samples is randomly selected and executed.

Each test person performs the contrast test several times during the whole test procedure. The test person is supposed to identify the orientation of the gap and click on the respective key on the keyboard which is labeled as illustrated in Figure 4–4. All information about the order of exposure of the Landolt rings, their orientation and their initial luminance for each test are saved in the respective info files and all information about the start up time for each test and subjective identification responses are saved in the log files at the performance time.

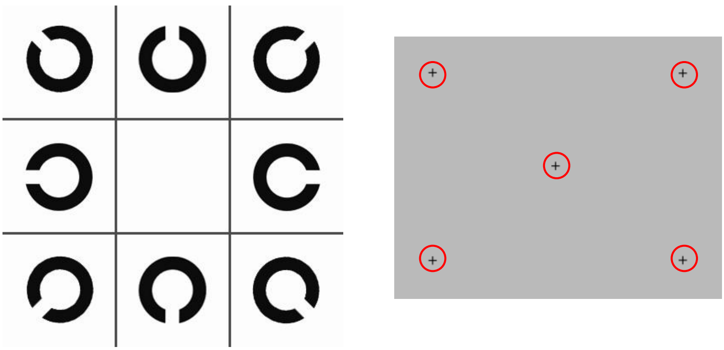


Figure 4–4: Left: All possible orientations for Landolt ring.
Right: five different locations on the monitor for exposure of the Landolt ring, before each exposure a black cross sign appears on the location to inform the user about the exposure location.

4.1.2.2 Evaluation of the contrast test

To evaluate the performed contrast tests, the following steps shall be implemented:

- Determining the initial luminance values of the fore- and background of each Landolt ring in all 100 available contrast tests (luminance before reflection). The Landolt ring images are generated randomly in different grayscales. To obtain the luminance value of each grayscale by exposure on the computer screen, various grayscale images are defined as screen-image and photographed by a CCD camera under dark-room conditions (see Figure 4–5). The luminance pictures that are taken are used to derive the luminance mapping functions for converting the grayscale values to luminance values and thereby determining the luminance of all Landolt rings and their background when being exposed on the computer screen.

- Computing the reflection luminance values on the computer screen whilst implementing the contrast tests; this is conducted using the fisheye luminance pictures taken every 30 seconds during the procedure. By means of the developed tool mentioned in *3.1.2.2- Image processing to derive reflection on screen"* the monitor screen in the fisheye pictures is detected and cut to be used for deriving the reflection luminances. The following procedure is implemented on the images of cut monitors to derive the reflection luminance for each contrast test:
    - The luminance values of the cut monitors are measured to be used as after-reflection luminances. Since the reflection could differ from area to area on the screen, the luminances of the 5 monitor areas (see Figure 4–6) are calculated separately.
    - The after-reflection luminances are compared with the reference picture (captured luminance picture from the background-image in dark room).
    - The luminance-differences between, after, and before reflection are saved as reflection luminances in the respective reflection files.

- Calculating the final contrasts of Landolt rings considering the achieved reflections. Each contrast test has an info file which includes the following information:
    - Test number
    - Exposure-position of each Landolt ring on screen
    - Gap orientation of each Landolt ring
    - Grayscale of each Landolt ring

  After converting the grayscale values to luminance values, the info files are modified and the luminances of the Landolt rings are stored. Afterwards the modified info files and reflection files of each contrast test are integrated and the final contrast ratios of all Landolt rings are computed by:

$$CR = \frac{L_b + L_r}{L_C + L_r} \qquad (4–1)$$

L_b: luminance of background [cd/m²]
L_C: luminance of Landolt ring [cd/m²]
L_r: reflection luminance[3] [cd/m²]

Furthermore the measure of the contrast threshold for each case is computed using the threshold contrast model defined in ISO 9241-303 (equation 2–8). The both computed contrast ratio and contrast threshold are compared for each Landolt ring to conclude whether the exposed contrast ratio is greater than contrast threshold or not. All obtained information of each contrast test is saved in a new data-file to be used in the next step.

- Evaluation of the subjective responses according to the achieved data-files. For this purpose the log-files are used. Log-files are the files which are recorded during each trial and include:
    - Performed contrast test number
    - Start up and response time
    - User response (pressed keys on the keyboard to indicate the gap orientations)
- In this step every log-file is compared with the corresponding data-file to determine whether the identified gap orientation is correct or not. The comparison outcomes are saved in new results files. The most important data in the result files which are to be evaluated for the purpose of this study are:
    - Contrast ratio of each Landolt ring
    - Contrast threshold of each Landolt ring
    - Contrast ratio lower or greater than contrast threshold
    - Identification record of each Landolt ring

[3] In this PhD study the used term of "reflection luminance (L_r)" includes all occurring reflection types on the computer screen. These reflection types have been described in the part *"2.3.1.1 Reflection and visual displays"* which depending on the screen type can be diffuse, specular and haze reflection. In the case of LCD we are usually confronted with all three reflection types. The mentioned L_r in this chapter is based on the measurement by CCD camera and includes all diffuse and specular reflection luminances ($L_r=L_D+L_S$; where, L_D is diffuse reflection and L_S is specular reflection).

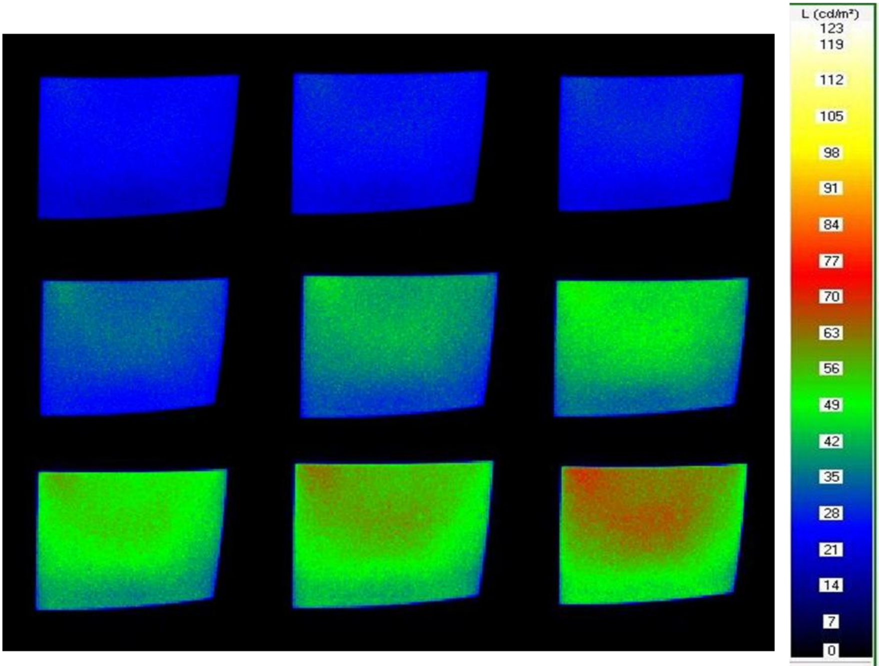


Figure 4–5: Luminance pictures taken from monitor with various grayscale images in dark room. This data is used to derive the luminance mapping function to convert grayscale values to luminance values. These illustrations are the false color images.

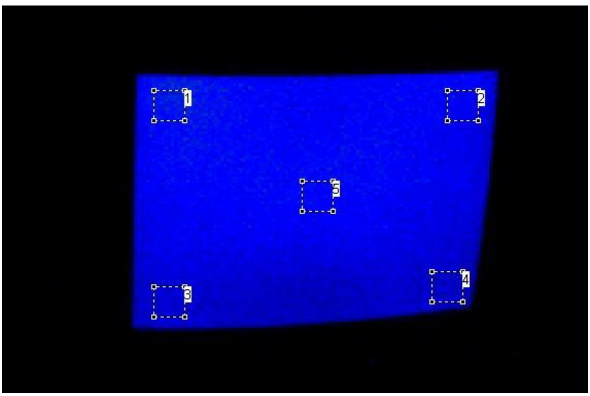


Figure 4–6: The luminance values of the five illustrated regions are computed in all cut monitors and also in a reference image taken in dark room from monitor to compute the value of reflection.

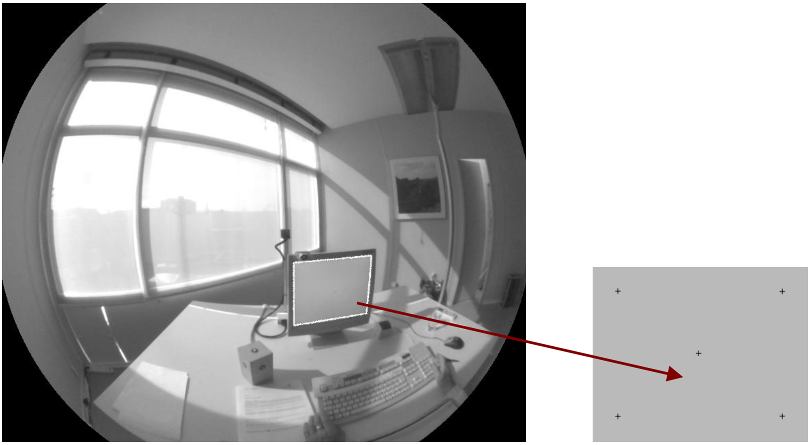


Figure 4–7: An example of the fisheye pictures taken every 30 seconds from the whole field of view by CCD camera which are used to determine the reflection luminances on the screen during each trial. The screen area in these images is cut and reformed by means of a tool which is developed for this reason.

The whole procedure is also summarized in a flowchart illustrated in Figure 4–8, divided into the procedure of generation on the one side and the procedure of presenting and processing on the other side.

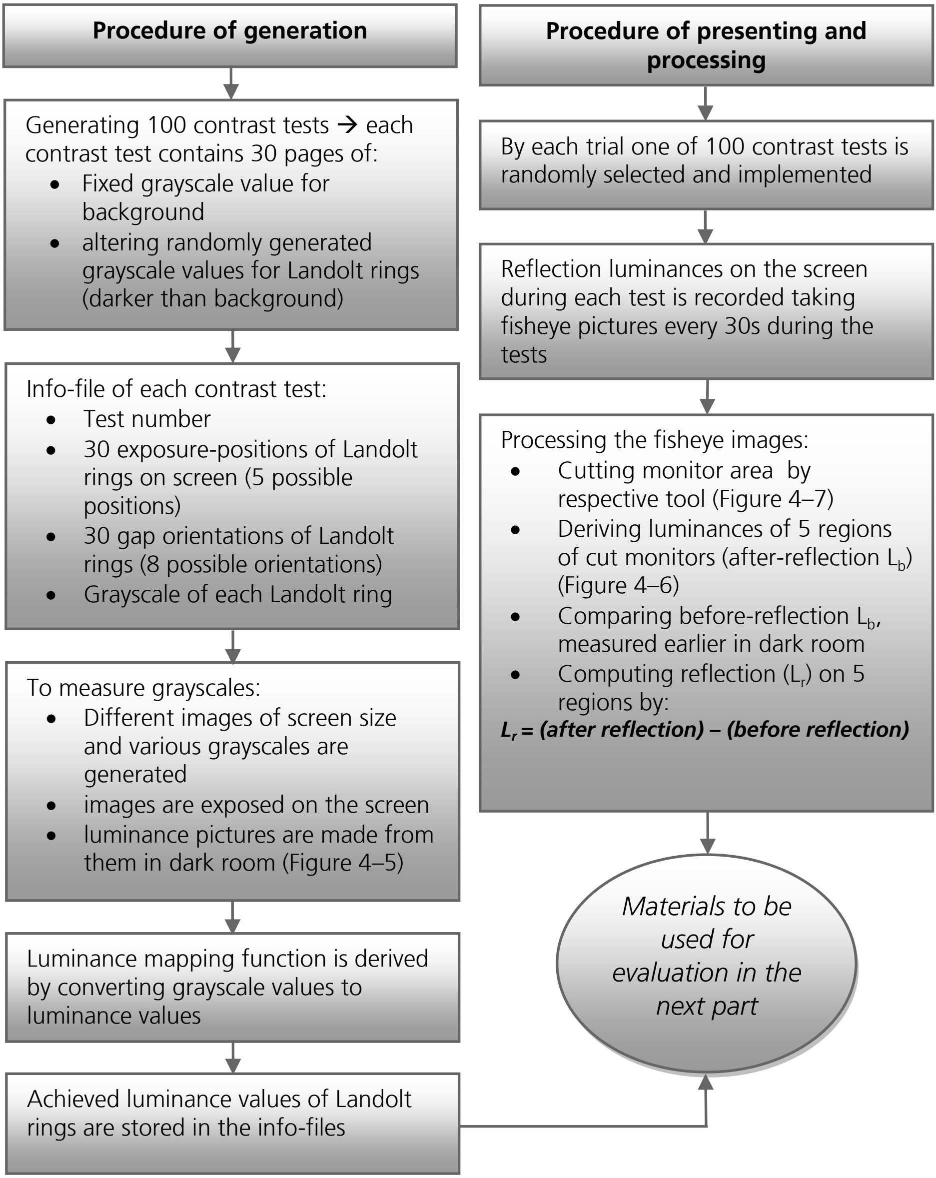


Figure 4–8: Flowchart describing the procedure of computing the luminance values of all Landolt rings and their background in the contrast test to be applied in evaluation.

Each contrast test after being performed includes:

- **Info-file**: test number; 30 Landolt rings positions(1-5); 30 Landolt rings orientations; 30 grayscales and corresponding luminances of Landolt-rings
- **Log-file**: test number; start up time; user response record (number of pressed key)
- **Reflection-file**: 5 reflection luminances on 5 screen-regions

↓

Integrating info-files with respective reflection-files for all performed contrast tests and make new data-files including:

- Final contrast of each Landolt ring $CR = \dfrac{L_b + L_r}{L_C + L_r}$
- Contrast threshold of each Landolt ring according to equation 2–8)

↓

Comparing the recorded log-files of performed contrast tests to the respective data-files of the tests and creating the **result-files** including:

- Final contrast-ratio of each Landolt ring
- Contrast-threshold of each Landolt ring
- Status of contrast-ratio of each Landolt ring comparing to contrast-threshold (lower or greater than contrast-threshold)
- Identification report of each Landolt ring (correctly recognized or not)

Figure 4–9: Flowchart describing the evaluation process of the contrast tests files using the information of Figure 4–8.

4.2 Results

The results of contrast tests in the next three series are evaluated with the following numbers of participants in each series (see the descriptions of test series in the part *4.1.1 Project methodology"*):

- First test-series or view-contact related series: 22
- Second test-series or brightness related series: 24
- Third test-series or age related series: 26

The entire observational data in each dataset to be evaluated for the purpose of this study are as:

- View-contact related series: 9659
- Brightness related series: 4530
- Age related series: 5280

It should be mentioned that every trial person performs the contrast test several times and each time a contrast-test is randomly chosen out of 100 generated sets and every contrast test includes 30 cases. This results in a great amount of data in any series. All of the obtained cases from all observers are put together for evaluation and the information of test persons is not taken into consideration. Although this could lead to a possible error as the data is not independent from each other, this method provides a wide range dataset of all possible contrast ratios (in the defined range) and helps support an appropriate evaluation possibility.

As the whole procedure in view-contact related series has been implemented two times (for two various outlooks) therefore the dataset of this series is larger than the other ones. It should also be stated that these datasets excluded failed and problematic cases (errors that occurred whilst performing or recording the tests).

The contrast between the Landolt rings and their background in all contrast tests are generally of low values and close to the contrast threshold. The current evaluations are to study the relationship between the subjective identification profile and standard contrast threshold (see equation 2–8). This is to find out whether the existing contrast threshold model would be compatible for use on a computer screen or not. As mentioned in "2.3.1.2-*Existing models for minimum required contrast*" the latest standard minimum contrast model for computer screens is based on the Kokoschka's contrast threshold, therefore the plan is to start the contrast evaluation for onscreen visual tasks with the underlying principle for the standard model i.e. the contrast threshold model.

4.2.1 Data evaluation

As mentioned in the above part, a huge amount of data is available in each dataset. To begin with the evaluation, a random grouping is formed to make data-groups of equal sample sizes[4]. This grouping process is in order to establish the probability of Landolt ring identification within each group. A sample size of 92 in the first test-series leads to 104 classes and in the third test-series leads to 57 classes. In the second test-series a sample size of 90 leads to 51 classes. In every class of 90/92 observational data, two following probabilities are established:

- Probability of identification determined by user assessments. This is the percentage of correct recognized Landolt ring cases by observers in each class.

[4] The number of observational data in each group is called sample size here.

- Probability of identification predicted by contrast threshold model. This is the percentage of Landolt ring cases with a contrast ratio greater than the contrast threshold in each class, which according to the model are supposed to be identified.

In the following diagrams, each data-point represents one of the above computed probabilities in each data-class (i.e. determined by user assessments or predicted by contrast threshold model). As visible in the diagrams of the first and second test-series (Figure 4–10 and Figure 4–11), the curves of the determined data by user assessments are different from the curves of the predicted data by contrast threshold model, this difference is mostly in the shape (rising from) of the diagrams. But in the diagram of the third test-series (Figure 4–12), the difference is more significant in respect to both form and magnitude. The third test-series is the age related series with observers of 50-70 years of age, while the test persons in the other two series are mainly from the age group of 20-30 years.

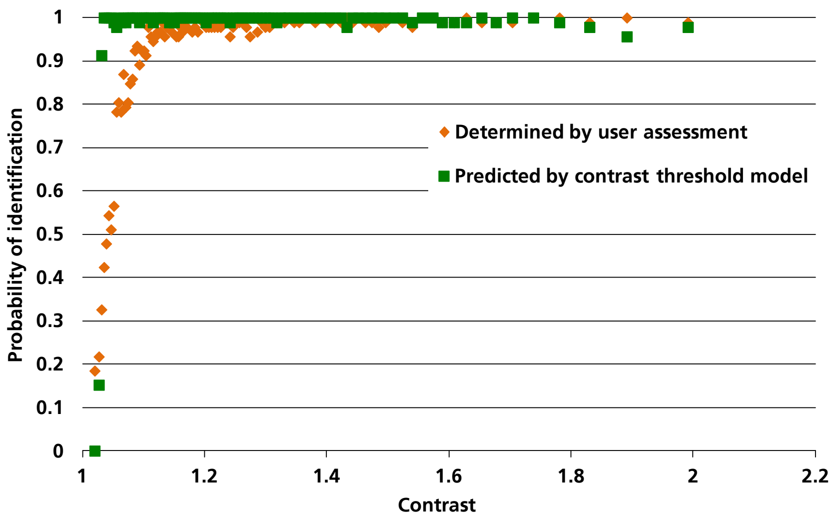


Figure 4–10: Comparison between probabilities of identification as determined by user assessment and as predicted by the contrast threshold model in the first test-series. Evaluation is conducted for 9659 observational data grouped in 104 classes. The probability of identification is established within each class.

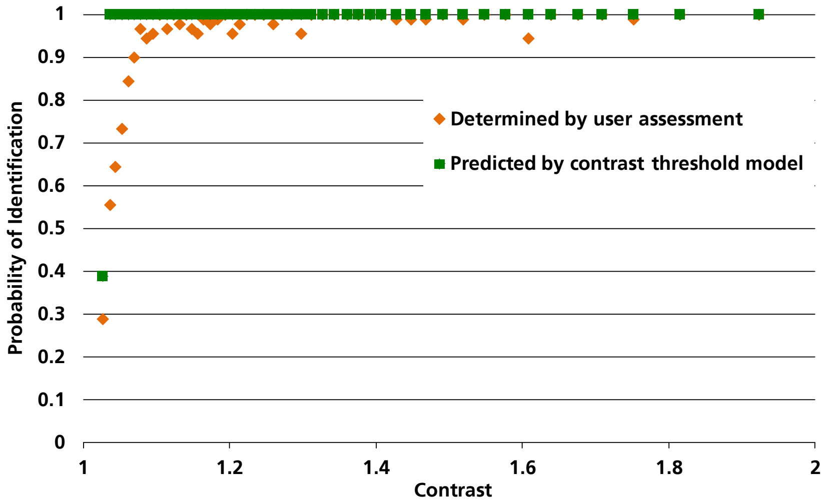


Figure 4–11: Comparison between probabilities of identification as determined by user assessment and as predicted by the contrast threshold model in the second test- series. Evaluation is conducted for 4530 observational data grouped in 51 classes. The probability of identification is established within each class.

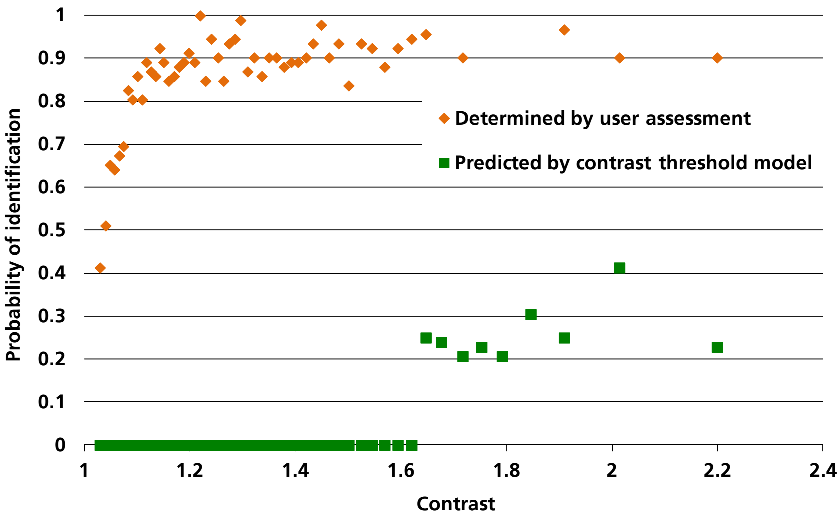


Figure 4–12: Comparison between probabilities of identification as determined by user assessment and as predicted by the contrast threshold model in age related series. Evaluation is conducted for 5280 observational data grouped in 57 classes. The probability of identification is established within each class.

Other statistical evaluations are conducted using those parts of the contrast tests that contain not identified cases or false identified cases (i.e. when the users could not correctly identify the gap in the Landolt ring). Between all of the contrast values under which the Landolt ring gap could not be identified, the maximum contrast values are selected to be applied to this evaluation. The hypothesis in this part is that, the more problematic lighting/surrounding situation is, the greater the contrast value would be under which the gap could not be recognized. To simplify the explanation the maximum contrast under which the gap could not be recognized is therefore called "maximum non-identified contrast". This part of the evaluation is performed using the data from the first and third test series. Within the third test series the age of the subjects is varied. The intention is to study the relation between contrast and age as well as the relationship between the subjective estimation of the screen and the maximum non-identified contrast. For this, screen quality related questions of the questionnaire are evaluated.

In Figure 4–13, the curves of maximum non-identified contrast for the age group of 20-30 years and the age group of 50-70 years are illustrated. As demonstrated in this diagram age has relation with the contrast level identification. Although within each group of subjects there is a noticeable interpersonal variance in maximum non-identified contrasts, but this variation for the subjects over 50 years of age is more evident. Figure 4–14 illustrates a Box-plot evaluation of the relationship between "maximum non-identified contrast" and "age" performed for the subjects of age related series. This shows that in the age group "60-70" the maximum non-identified contrasts are generally higher than in the age group"50-60" but interpersonal variation is also noticeable.

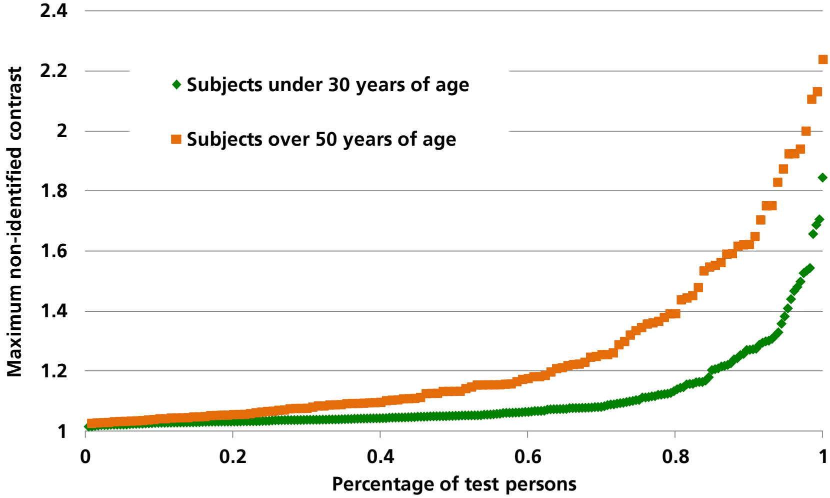


Figure 4–13: Diagram of maximum non-identified contrast value for two age groups. The number of data in age group 20-30 is 233 and the number of data in the age group over 50 is 130.

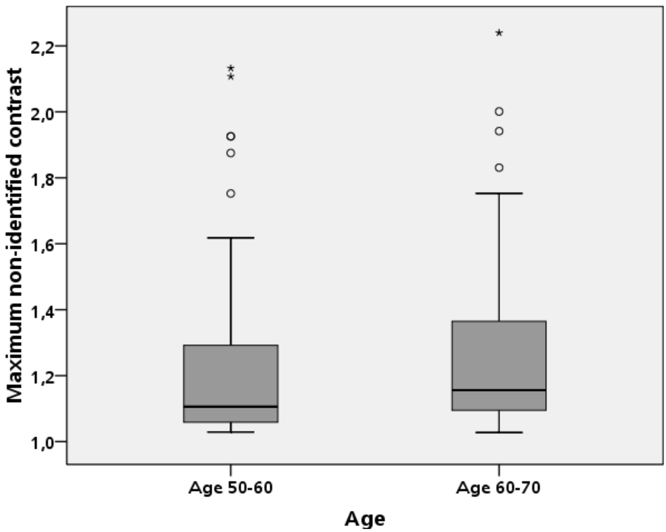


Figure 4–14: Box-plot presentation of the relationship between "maximum non-identified contrast" and "age" for the age related series. The boxes represent 50% of observational data within the relevant group and the horizontal lines above and below the boxes represent the limit of the entire data except for the outliers illustrated as extra points.

As demonstrated in Figure 4–15, “maximum non-identified contrast” and subjective estimation of being “bothered by reflection on screen” in the first test-series have a relation. By increasing the value of “maximum undetected contrast”, users are more “bothered by screen reflection”. Figure 4–16 shows the relationship between “maximum non-identified contrast” and subjective estimation of “lighting level on screen” in the age related series. There is a relation between the subjective ratings of light level on the screen and the maximum contrast value not identified by them.

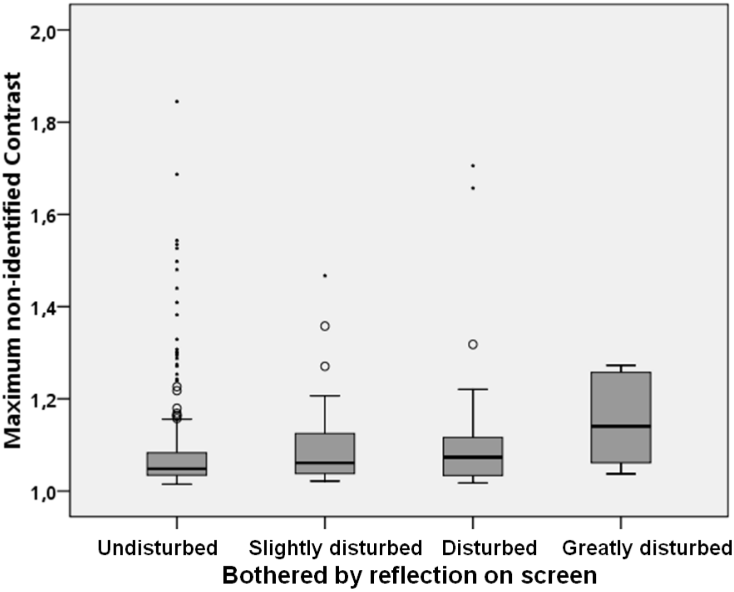


Figure 4–15: Box-plot presentation of relationship between “maximum non-identified contrast” and the subjective estimations of screen in the first test-series. The original question for this evaluation is „were you bothered via reflection on screen” and the observers can rank their estimation on a linear scale from "not at all" to "very much"[5].(see Appendix B) For this evaluation the ranking lines are divided to four categories (stated on the X-axis of the diagram). Boxes represent 50% of observational data in each category and the horizontal lines above and below the boxes represent the limit of the entire dataset except for the outliers which are illustrated as extras.

[5] The original text in German language is: „wurden Sie gestört durch Spiegelungen auf dem Bildschirm“ with the ranking level from „Gar nicht“ to „Sehr“.

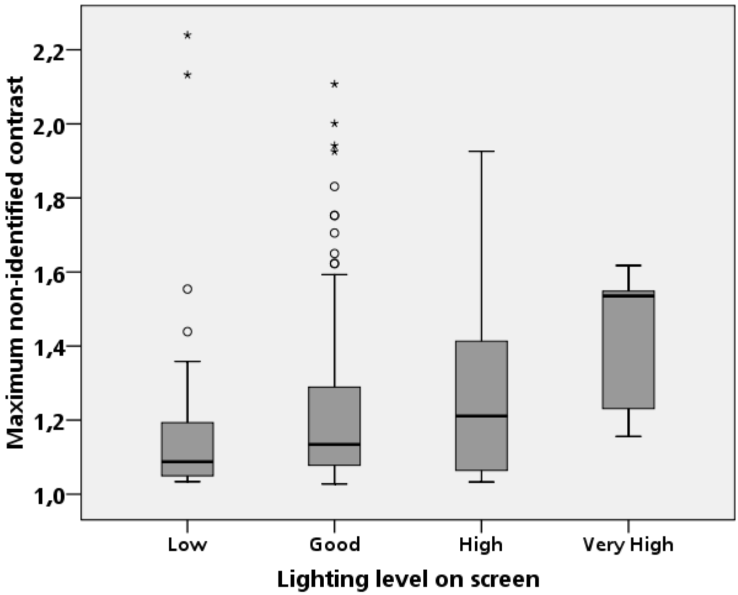


Figure 4–16: Box-plot presentation of relationship between "maximum non-identified contrast" and subjective estimation of the lighting level on screen in age related series. The original question for this evaluation is "how do you estimate the current lighting level on the screen?" while the observers can rank their answers with a linear scale from "very low" to "very high"6 (see Appendix B). For this evaluation the ranking lines are divided into four categories (stated on the X-axis of the diagram). Boxes represent 50% of the observational data in each category and the horizontal lines above and below the boxes represent the limit of the entire dataset except for the outliers which are illustrated as extras.

4.3 Discussion and Outlook

The main part of this chapter is the attained results of the comparison between both the predicted (by standard contrast model in equation 2–8 and the observed (from user assessments) probability of identification. For this purpose the datasets are grouped in classes of similar sample size to establish a probability within each group. This evaluation shows that the contrast threshold model does not have a good agreement with the subjective identification in this study. As demonstrated in Figure 4–10 to Figure 4–12 the rising forms of the observational data are dissimilar to the predicted data by

[6] The original text in German language is: „Wie bewerten Sie das jetzige Beleuchtungsniveau zum Tippen eines Textes am PC?" with the option of „Das Beleuchtungsniveau auf dem Bildschirm ist" and the ranking level from „zu niedrig to „zu hoch".

model. This disagreement is more noticeable for the subjective results in the age group of 50-70 years by which the percentage of identified and predicted cases are considerably different. According to the results of this study the threshold contrast model underestimates the identification ability of the older age groups. Therefore it can be assumed that the considered age effect is too strong which is mainly due to the application of the Blackwell age multipliers (Table 2-1). Other evaluation performed to assess the effect of age on the contrast sensation within the current study which shows that despite the interpersonal variations, age is an important factor in contrast perception (Figure 4–13 and Figure 4–14).

Furthermore a Pearson correlation evaluation is performed between all the observed data (probabilities of identification) in all three series of outlook, brightness and age and the predicted data by threshold model. The result shows a Pearson Coefficient of 31% which is a weak correlation factor. One of the obvious reasons for this weak correlation is age [7] and other potential reasons could be that the threshold contrast model (equation 2–8) is a function of low state luminance and size of visual target and other parameters such as adaptation luminance of the eye (or ambient luminance) have not been considered in the model. The ambient luminance of the current experiment is different from the experimental study based on which the contrast threshold model has been developed (Study performed by Blackwell stated in [12]) and this could result in different outcomes. On the other hand the visual task and other test conditions of that experimental study have been different to the current experiment which is in office conditions. Hence, the weak correlation factor in this study is supposed to be a combination-result of the all mentioned reasons.

The latest ISO-standard model for minimum required contrast is based on the evaluated contrast threshold model (see *2.3.1.2- Existing models for minimum required contrast*"). Hence, this evaluation shows that the standard contrast model does not fit to the user responses within the scope of this research study. Apart from the main evaluations, some other preliminary assessments are also performed on the "maximum non-identified contrast" obtained from contrast tests and the subjective estimation of the screen quality. As visible in Figure 4–15 and Figure 4–16 the attained relations in this regard indicate that contrast could be a significant factor to improve the visual comfort while

[7] Considered age factor for contrast threshold model (equation 2–8) is based on the suggested age factor in the latest standard for minimum required contrast for working at visual displays [36]. This age factor has been proposed by Blackwell and Blackwell [14] and is stated in Table 2-1.

working on computer screens. This outcome could be considered as additional proof beside the conclusion of the chapter-3 for relationship between contrast and subjective estimation of screen quality.

However, it should be mentioned that some non-identified cases in the described tests, could have been occurred due to the reasons other than contrast, such as pressing the wrong keys. Since within this study it was not possible to filter the error associated non-identifications from the contrast associated ones an additional investigation into this aspect is considered as beneficial in order to reduce potential error factors.

The conclusions of this chapter can be summarized in the following points:

- Contrast threshold model does not fit the subjective results of this study especially for the older age group.
- Age of the people has an effect on their identification ability; however this effect has been overvalued in the existing standard model.
- Users' contrast perceptions show relation with their estimation of visual quality of the screens when they are performing a visual task (contrast-test).

5 Experimental study to evaluate contrast and readability on VDTs[8]

5.1 Method

After testing the main defined hypothesis of this research regarding the "relevance of veiling glare method to evaluate the visual quality of visual displays" in chapter-3 and concluding that the existing contrast model is not a reliable basis for veiling glare study on computer screens in chapter-4, the next step of the research would be to propose a reliable basis for the research hypothesis.

In other words, a method based on contrast could be an appropriate method for evaluating screen visibility in office spaces and for an accurate contrast assessment in this regard it is necessary to avail a validated model for "minimum required contrast". The literature review (see "*2.3-Veiling glare*") showed that beside the existing ISO models for readability of displays, only a few studies have been so far undertaken. Moreover, the latest ISO model [36] is based on an old experiment, with a set-up totally different to today's office spaces [12] and the underlying "contras threshold model" (equation 2–8) for this standard showed a weak correlation with subjective results achieved within this research (chapter-4).

Therefore the current study aims to set up an experiment in a real office environment and with office-like visual tasks, in order to evaluate the minimum required contrast for performing onscreen visual tasks. The main purpose is to improve the existing standard model or to develop a new model.

5.1.1 Project methodology

The reason for conducting this part is a hypothesis that the existing standard model does not correlate to the observed data (chapter-4) because of the underlying experiment which was performed under conditions far removed from real conditions (working with visual displays in an office room). Due to this hypothesis the purpose of this chapter is to study the contrast perception or preference of the users under conditions closer to real office conditions whilst working on computer screens by parameterizing the factors which could

[8] This experimental user assessment study has been performed as a Master Thesis which was defined and completed within the framework of the current research work and was supervised by the author of this Ph.D. thesis. Most of descriptions in the subchapter "Method" regarding the procedure of designing and conducting the experimental tests are based on the work performed within this thesis [65].

influence personal contrast perceptions. The whole process of the experiments can be summarized in the following three steps:

- First step of the study is designing and preparing the experimental procedure. This step consists of designing a user assessment test to investigate the contrast perception/preference of the test persons. According to the hypothesis of the experiment it should be closer to real on-screen visual tasks in offices and the parameters that are assumed to influence the contrast perception such as ambient brightness, age, polarity of the displayed image on computer screen, are taken into consideration in the design phase.
- Second step is to perform the user assessment tests under daylight and artificial lighting conditions. Daylight results in varying degrees of ambient brightness and also causes reflection on the computer screen that results in contrast reduction of the visual task. This reflection-related contrast reduction is an important aspect that should be considered in this experimental study under the hypothesis which is to develop a model under real conditions. The experiment includes different parts which are carried out in the rotatable office-like test rooms.
- Third step is statistical analysis of the obtained data and performing a correlation study between the standard minimum contrast model and the obtained dataset from the new user assessments.

5.1.1.1 Selection of experimental method

There are different possibilities for conducting the user assessment study such as:

- Real office
- Office like test room
- Virtual reality device

All of these options have the potential to fulfill the desired test-conditions of the defined hypothesis. In other words, in all of the above mentioned methods, the users can perform the tests under situations close to the real office. Even virtual reality devices have the ability to simulate a visual environment so that the test persons experience the comparable visual-conditions with real offices.

To start with the real office option was excluded due to the fact that in the real office it would be very complicated (almost impossible) to afford comparable conditions for different test persons and to control all of the test conditions. Therefore the decision process is focused on the other two options. In the case of office like test room, the experiments and measurements are implemented in a test room which is arranged similar to a real office room and under real daylight situation. The testing subjects perform the office like visual tasks. This type of study is very realistic, but it can be very time consuming. Furthermore, it is not easy to have full control on different variables like environmental brightness, daylight and weather conditions.

The third option is using a virtual reality device as an assessment method. For this purpose a “Stationary Virtual Reality” (SVR) device is available which has been developed within the framework of a former research study [81]. By means of this apparatus it is possible to create a high resolution stereo projection in order to generate a realistic impression of simulated scenes [79, 81]. As illustrated in Figure 5–1 two images are projected on to a screen located close to the eye position to create a stereo effect. By applying this method it is possible to generate exactly the same conditions for each subject. Another advantage of virtual reality method is the possibility of providing a stable daylight condition for a longer period of time, while in an office like test room such an arrangement would not be possible. In addition, the distance between eye position and monitor would be always fixed in this method.

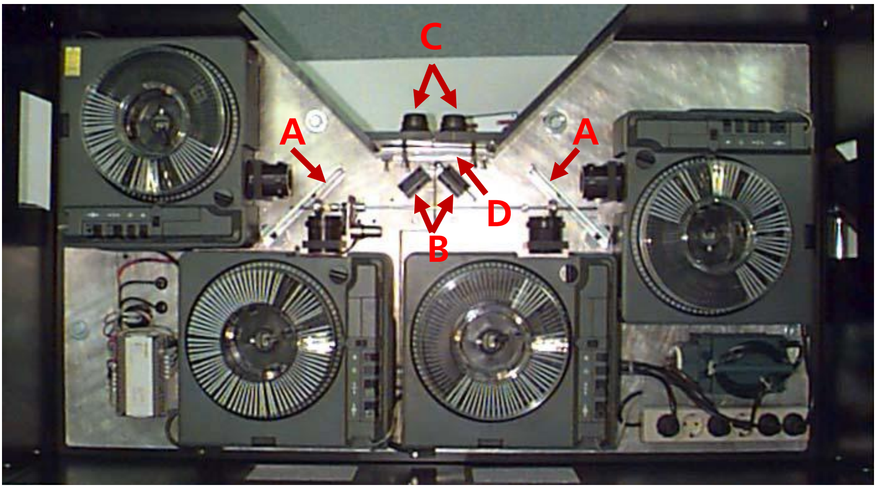


Figure 5–1: Top view of a SVR apparatus. A: moving mirror B: fixed mirror C: ocular lenses D: projection foils. Four slide projectors afford the smooth transition of the different images. The mechanism is based on a stereo projection to make a 3D presentation of the images to the observer who looks through the ocular lenses “C” [79, 81].

But despite the mentioned advantages there are problems, due to which using virtual reality method would be complicated and not practical. SVR apparatus works with rear projection which causes absorption and scattering of the light passing through the screen. This leads to the loss of sharpness of the final image. In this study which is based on a reading task sharpness is an important factor and cannot be neglected. The existing foil in the SVR is a polyethylene foil from "National Plastic Packing", Dublin with the thickness less than 0.1mm, but the achieved sharpness with this material is not enough to represent a sharp reading task on the screen. Table 5-1 shows a comparison between the two methods with advantages and disadvantages of both sides.

Table 5-1: Comparison between the test room and SVR method with advantages and disadvantages of both methods.

Comparison Point	SVR	Test room
Stability of environmental and daylight conditions	+	-
Resolution of visual display	- (lowest possible view angle for one pixel =3.5´)	+
Image sharpness	-	+
View distance fixation	+	-
Luminance measurement at the view point	+	-
Maximum luminance value	- (Up to 9000cd/m^2)	+

Considering the mentioned complications by using virtual reality method which are not easily resolvable within the scope of current research, it is decided to perform the user assessments in the office-like test rooms. The available test room which is to be used for the purpose of this experimental study, is a rotatable container consisting of two office like spaces located on roof of ISE building is describes thoroughly in the part "*5.1.1.4.- Experiment facilities*"

5.1.1.2 Selection of test persons

A parameter which is intended to be evaluated in this study is age. Age is supposed to be an affecting factor in contrast perception. Therefore the subjects are selected from the following three age groups:

- Age group 1: 20-30 years old; 15 subjects
- Age group 2: 40-50 years old; 15 subjects
- Age group 3: 60-70 years old; 15 subjects

All of the test persons are untrained. Age group1 is from the ISE employees while the age groups 2 and 3 are assigned and invited to ISE for this purpose. The persons with eye disease are excluded from this study.

5.1.1.3 Reading test design

Reading procedure is a combination of saccades and fixations. Saccades are defined as the short eye movements whilst going through a text and fixations are described as the pauses between the saccades [41]. To evaluate reading performance there are several methods which are used for different reasons. For example, reading acuity is used in eye clinics and is measured by the smallest readable print; the main applied method in education for this reason is reading comprehension. Reading speed is a value which is measured in word per minute (wpm) and has been broadly used in psychophysical fields because it can be measured objectively, it is reproducible and sensitive to variations in visual parameters [41]. Reading speed can be used to evaluate both educational and perceptual aspects of reading [41, 43]. Therefore it is decided to apply reading speed as a measure for assessment of visual performance in this study. There are three methods for computing personal reading speed which are explained in the following:

- **Drifting method**

In this method the text sweeps from the left edge to the right edge of the display. Before starting the test the first letter is visible at the right margin and after the warning and by pressing the respective button the sweeping of a text-line starts. The sweeping ends after the last character of the line on the left margin disappear. The test person is required to read the text aloud and the person conducting the experiment counts the mistakes or missed words using a fair copy [41].

- **RSVP**

RSVP is abbreviation of “Rapid Serial Visual Presentation”. RSVP is the successive exposure of individual words at the same position on the screen and the speed can be controlled by adjusting the exposure time for each word. The test person is required to read the exposed words aloud. In this method the role of the eye movement in reading is neglected and is actually a cognitive study of word recognition in reading [41].

- **Flashcard method**

In this method different slides of texts appear on the screen for varying amounts of exposure time. The subject is required to read the text aloud, as quick as possible and without missing any words. The exposure time decreases until the subject is not able to read the whole text anymore [62].

Among the three described evaluation methods for reading speed the flashcard method is selected for the purpose of this study because the other two methods (Drifting and RSVP) do not represent the normal reading process. The main disadvantage of drifting method is the elimination of the individual fixation time in reading while the RSVP method does not consider eye movement in the reading process. Therefore, the flashcard method has been chosen as it resembles the normal reading procedure more than the others.

In the flashcard method the flash slides should contain a predetermined number of words or sentences. For designing the slides appropriately, there are some important points which should be discussed in order to make a proper decision:

- Number of the words or sentences in a slide
- Content of the sentences
- Arrangement method of the words

To discuss the above mentioned points it is first necessary to assess the factors which could affect these points. These factors are described in the successive part.

✓ **Eye movement**

As mentioned before the reading procedure is in fact a combination of saccades and fixations and despite our perception, our eye does not have a smooth movement along the text by reading. This is due to the fact that in vision process, high detail recognition happens just in a narrow view angle. The eye movement could be an affecting aspect in designing the text content because the configuration of the visual stimuli affects the pattern of eye movement [43]. In order to support similar eye movements by reading all the flash slides, it was decided to generate the slide-texts using the set of words with certain characteristics:

- Each word consists of 3-7 characters which cause it to be recognized in one perceptual span[9].
- All the words are from the German language which is the native language of the subjects.

[9] In an alphabetic text, readers can progress at a normal speed when there are14 to15 characters on the right side and 3 to 4 characters on the left side of the fixation point. However, word recognition probably does not extend to more than 7 or 8 characters to the right of the fixation point. It is very likely that the fixation point coincides half way into the word [62] So, by considering the word size of 3-7 characters and the fixation point on the word-centre, each word does not have more than 3-4 characters on the left side of fixation point and therefore the whole word would be recognized in one perceptual span.

- ✓ **Reading method (oral or silent)**

In all three reading test methods the text is read aloud. Oral reading is a proper method for objective measurements due to the recording approach which is done by the person conducting the experiment. The disadvantage of this method is its difference from normal reading behavior. Conducted studies on silent and oral reading parameter demonstrate that the results of silent and oral reading rate achieved with the flashcard method for short texts are very similar [40]. By oral reading test we might be confronted with the phenomenon of eye-voice span which happens when the voice would be delayed by the reading act. But in the case of short texts, the text is preserved in the short term memory and the voice is just an indication of the correct words read and therefore this phenomenon would not affect the test procedure [41]. This is a reason for designing the reading test with short text slides.

- ✓ **Text complexity**

The difficulty of the text could significantly affect the reading speed and as this is non-visual it is an undesired effect for this study. To eliminate this effect the level of the text should be lower than reading ability level of the subjects. For this reason it was decided to generate the word database from the book of a 3rd grade German primary school in order to have a text level lower than the subjective reading level.

- ✓ **Selection of the character size**

According to the recommendation, the minimum Latin character height shall be 16 minutes of arc. For applications where legibility is secondary to the task, smaller characters may be used (for example, for footnotes, superscripts and subscripts). For Latin characters, the character height should exceed 10′ of arc unless loss of readability is acceptable (e.g. when showing page layout appearance) [36].

Furthermore, for a good legibility of constant text, character height should not be smaller than 14′ or larger than 22′ of arc. Too small characters cause problems by characterizing a word while too large characters increase the fixations and disturb the normal reading process [61].

As for the aim of this study it is better to evaluate the reading performance for extreme cases, hence the minimum recommended character size is selected which is equal to 14′ of arc. The relationship between the character height and pixel size of visual display can be formulated as [27]:

$$\psi = \frac{\left(180 \times 60 \times V_{Pitch} \times N_{H,Height}\right)}{\pi \times D_{View}} \tag{5–1}$$

Ψ: character height [minute of arc]
V_{Pitch}: height of a pixel [mm]
$N_{H,\ Height}$: height in pixel
D_{view}: distance from the display [mm]

In the case of the monitor used for this study with the dimension of 340mm x 275mm and considered resolution of 1280px X 1024px, the height of a pixel is equal to: V_{pitch}= 0.26mm. According to recommendations the preferred viewing distance for the visual displays using in office spaces should be in the range of 400mm to 750mm [35]. Therefore, for this study a viewing distance of 600 mm is considered which is in the standard range. Using the computed V_{pitch} and assumed view distance in equation 5–1 would result in the following dimension for the selected character size: Ψ =14'=2.5mm.

- ✓ **Selection of font type**

The type of font which would be selected for the reading test could affect the achieved reading rate result. Legge compared two common used fonts i.e. “Times New Roman” and “Courier” in this regard. The results show that the achieved reading rates with “Courier” are higher than “Times New Roman” for both normal and low vision observers [45]. The selected font for the purpose of this study is “Courier New” which has a clear and appropriate layout for eye movement. This font is Serif type with little legs on the edges. Serif fonts improve the text readability due to their structure which helps to distinguish the characters [78].

Mai Uhr Tod Sehr	Mai Uhr Tod Sehr	Mai Uhr Tod Sehr
Tausend Sie fünf	Tausend Sie fünf	Tausend Sie fünf
Abend Ihr violett	Abend Ihr violett	Abend Ihr violett
Nie Sommer Juli	Nie Sommer Juli	Nie Sommer Juli
Winter Nur schön	Winter Nur schön	Winter Nur schön

Figure 5–2: Three font example: Times New Roman, Courier New, and Arial in sets of unrelated words [65].

- ✓ **Content of text**

The content of the text could be an important factor affecting the subjective reading rate. Meaning of the text can create a mental process such as perception and reasoning which could influence the reading procedure. For example, the meaning of a sentence might be related to previous experiences and results in the person estimating the rest of the text without reading it thoroughly or more likely thereby increasing the comprehension time and consequently decreasing the reading speed [41]. According to the mentioned complications of using meaningful sentences it was decided to use unrelated words instead of sentences for this study. A template is to be designed for this reason could be used for all of the considered word sets in this study. According to the conducted literature study regarding the short text slides, sets consist of 5 rows and each row including few unrelated words shows to be an appropriate format. To have an even design for all slides each row is considered to include 16 keystrokes. This amount of keystroke could be generated via a combination of 3 to 4 words with the size of 3-7 characters.

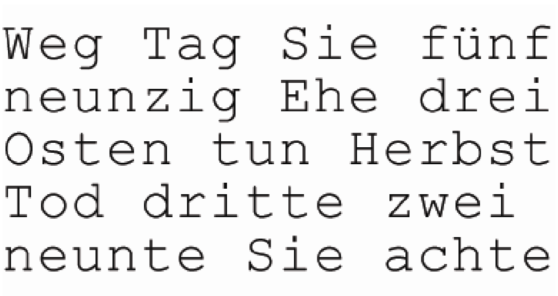


Figure 5–3: An example of a flash slide generated according to the designed template consisting of 5 rows of unrelated words; each row includes 16 keystrokes.

✓ **Instruction**

Designing the instruction to be given to the subjects before starting the tests could have an important effect on their reading speed. For instance an instruction like "read at your ordinary pace" would result in lower reading rate compared to an instruction such as "read at maximum possible speed"[65]. Legge applies instruction such as "Read as quickly and accurately as you can, keeping errors to a minimum…" in his reading tests based on flashcards [41, 42]. Since the reading tests of the current study are also based on flashcard method it was decided to use the same instruction.

✓ **Procedure designing**

After deciding to use flashcards as the reading test method the next steps are to be followed in order to generate the desired flashcards:

- Creating a databank of 416 German words containing the words with 3 to 7 characters from the book of 3rd grade primary school.
- Generating several word sets of five rows with any row including 16 keystrokes. The generation order is random.

- Considering 18 different luminance from black to light grey and making the word sets with all considered luminance values.
- Creating flash slides with white and black backgrounds and word sets of different luminance values.

5.1.1.4 Experiment facilities

I. Testing rooms

The daylight laboratory used for the current experiments is the same as described in the *"3.1.1-Project methodology"*, i.e. two similar neighboring test rooms placed on the roof of the main building of the Fraunhofer Institute for Solar Energy Systems (ISE). The windows of the test rooms are adjustable in different sizes from the fully glazed façade to a small size window. But for this study just one window size is used which is the one illustrated in Figure 5–4. The window façade in one of the rooms is covered with a color-neutral foil which reduces the transmission of the glazing by up to 8%. This would be helpful in order to provide low ambient brightness for one part of the tests.

Figure 5–4: A photograph of the daylight laboratory from outside. The illustrated window size arrangement is used for the current experiment.

II. Illuminance sensors

Several illuminance sensors or lux-meters are used in order to measure the indoor illuminances. The lux-meters are used in the following locations to monitor the illuminance values every 10 seconds:

- Work plane: fixed on the desk with height of 0.85 m from floor
- Monitor corner: on the upper left corner of the monitor
- Eye position: on a tripod as close as possible to the observer's eye position to measure the vertical illuminance at eye level.

The measured illuminances are not required to be used directly in the evaluations. These measures are saved to be applied as reference in the case of necessity.

III. CCD camera

The luminance distribution in the field of observer's view and on the visual display is measured by means of a calibrated scientific-grade CCD camera from TechnoTeam (LMK 98-4 color). This camera is mounted on a tripod close to subject's eye position directed towards the monitor. The lens for this measurement is a fisheye lens. The camera captures pictures automatically from the whole view field every 30 seconds.

IV. Other test requirements

✓ Visual Display

The monitor used for this experiment is a flat panel LCD TFT, type EIZO FlexScan L56 LCD, which is a commonly used type of monitor in office spaces. This is a 17inch display with a maximum resolution of 1280 x 1024. According to manufacturer discretion this visual display is supposed to offer the maximum brightness of 230 cd/m^2 and maximum contrast ratio of 400/1.This display is certified according to ISO 13406-2 (standard for visual ergonomic) and according to TCO99 it emits little radiation [67]. This device is the available visual display in the daylight laboratory and though other newer monitor types in the market might have lower reflection compared to this one the test procedure is performed using this computer screen because of the following reasons:

- The concept of this study is to develop a model for required/preferred contrast while working with visual displays; the type of display is out of the scope of this study.
- The photometrical property of visual displays e.g. better or worse reflection behavior could not affect the results of this experimental study. The purpose is to evaluate the final contrast of displayed text after reflection; many different final contrasts (due to many different lighting conditions) are generated and studied which can occur on any screen type.

✓ Headrest and the keyboard

A headrest is designed and built in order to fix the distance between the subjective view point and computer screen. Fixing the viewing distance has two advantages:

- Preventing undesired changes in the angular size of the characters

- Preventing undesired changes in the view direction and consequently in perceived luminance of the monitor

In the test procedure trial persons are required to give some signals e.g. for switching to the next part after finishing a part or for revealing their opinions about comfort by pressing a button. For this reason the keyboard is programmed to receive these signals via certain specified keys. The respective keys are labeled with colorful labels which are described in the instruction given to the subjects.

✓ **Luminaire**

Some parts of the experiments are implemented under artificial lighting conditions. For this purpose a luminaire is used which could be adjusted to emit different levels of light. The luminaire is a freestanding type from "Waldmann Lighting" called TYCOON. This type is a direct/indirect luminaire using T5 fluorescent lamp technology (See Figure 5–6, left).

✓ **Voice recorder**

A digital voice recorder, type "Sharp PAVR10E", is used during the test to record the voice of the trial persons while reading aloud from the flash slides. These records will be used later in order to check the accuracy of the reading mistakes which are marked on the fair-copies by the person conducting the experiment during the reading time.



Figure 5–5 : Left: LCD Monitor and lux-meter on its corner.
Middle: CCD camera to take fisheye pictures every 30 second and a lux-meter to measure illuminance at eye level both mounted on a tripod.
Right: CCD camera to take single luminance pictures before and after each trial.

Figure 5–6 : Left: Freestanding direct / indirect type of luminaire using T5 fluorescent lamp technology.
Right: Modified keyboard with colorful labels on specified keys to receive the subject's signals whenever necessary.

5.1.2 Experimental Procedure

This experiment consists of three main parts:

- **Eye sight screening:** determining the visual acuity and contrast sensitivity of the subjects under dim light conditions.
- **Testing under artificial light:** based on the developed reading test in order to determine the personal reading acuity and subjective contrast perception and comfort level by conducting onscreen task without daylight related reflection on the monitor:
    - **Phase 1**: measurement of personal reading acuity.
    - **Phase 2**: evaluation of subjective contrast perception for reading tests with positive text polarity.
    - **Phase 3**: evaluation of subjective comfort level for reading tests with positive text polarity.
    - **Phase 4**: evaluation of subjective contrast perception for reading tests with negative text polarity.
    - **Phase 5**: evaluation of subjective comfort level for reading tests with negative text polarity.
- **Testing under daylight conditions:** based on the reading test in order to evaluate the subjective contrast perception and comfort level by conducting on-screen tasks considering daylight associated reflection on the monitor:
    - **Phase 2**: evaluation of subjective contrast perception for reading tests with positive text polarity.
    - **Phase 3**: evaluation of subjective comfort level for reading tests with positive text polarity.
    - **Phase 4**: evaluation of subjective contrast perception for reading tests with negative text polarity.

- **Phase 5**: evaluation of subjective comfort level for reading tests with negative text polarity.

Before starting the process the subjects are given a short introduction and instruction to become aware of the whole experiment (see Appendix C). As mentioned above both positive and negative text polarities are to be tested in this experiment. Positive polarity is the exposure of dark text on a brighter background and negative polarity is vice-versa (bright text on the dark background). It is possible that the subjective readability and contrast perception would be different for different text polarities and it was therefore decided to consider polarity as a parameter in this experiment to be evaluated.

The experiment is performed in all three age groups. From the 15 subjects in each age group, seven are tested in a darker room with the glazing façade where transmission is adjusted to 8% by means of color-neutral foils. The other 8 subjects are tested in a brighter room with the normal window façade of 54% transmission.

5.1.2.1 Part 1-Visual acuity test

The first step is eye sight screening of the test persons. The purpose is obtaining the visual acuity and contrast sensitivity of the subjects before starting the main test and eliminating the people with abnormal vision[10]. Visual acuity is defined as:

$$VA = \frac{1}{d_t} \qquad (5\text{–}2)$$

VA: visual acuity

d_t: threshold gap size [minute of arc]

Gap is the broken opening in the Landolt C, optotype. The threshold is defined as the detection rate against the size of optotype which is described by a psychometric function [3, 4, 2].

The visual acuity of the subjects are measured by means of a computer program called FrACT (Freiburg Visual Acuity and Contrast Test), which has been developed by Michael Bach at the University Eye Clinic of Freiburg [2].In order to measure the visual acuity of the observers by FrACT, Landolt C (Landolt ring) is used as an optotype and the task is to recognize the orientation of the gap in the Landolt C exposed on the monitor. A response

[10] The subjects are asked to use their reading glasses or contact lenses if necessary during the whole test.

box[11] enclosing eight buttons labeled with all possible Landolt ring orientations is handed to the subjects for selecting the correct optotype orientation after each exposure by pressing the corresponding button. The procedure starts with a large optotype which is easy to recognize and depending on the response the next presented optotype can be easier or more difficult to recognize. The purpose is to determine the spatial resolution limit or threshold. The threshold recognition rate is set in the middle of 100% and guessing rate (12.5% in the case of 8 choices) i.e. at 56.25%. That means at the "acuity value" almost half the optotypes are not correctly recognized [5].

The visual acuity of the subjects should lie in the range of $0.8<VA<2$ to be acceptable for this study. Another parameter which can be measured by FrACT is contrast sensitivity. Contrast sensitivity is a personal measure that shows the ability to distinguish between different levels of luminance and is dependent on the spatial frequency of the image to see and its peak between 2-5 cycles/ degree [77].

The lighting condition for conducing visual acuity test should be (according to EN ISO 8596 [28]) based on which luminance of the task field should be between 30 and 320cd/m^2. The task field is the monitor screen which with an average luminance of about 148cd/m^2 falls into the recommended range. Furthermore, based on the same standard no light source and no bright surface with either glossy or matt material shall be present in the visual field for such measurements. These requirements are also met in this part. Also the recommended average ambient luminance for a task field with such an angular size as the current study (about 28°) is between 0.01cd/m^2 and the task field luminance. During the current test, the ambient luminance is 60cd/m^2 which is within the standard range. The distance between the observer and visual display is set to two meters to meet the regulation in the same standard.

The visual acuity test is implemented four times with the first time counted as training, to confirm the reliability of the results. After visual acuity the contrast sensitivity is tested under identical settings but without the training round.

5.1.2.2 Part 2-reading test under artificial lighting

After completing the eye sight monitoring and insuring that the selected subjects are in the acceptable visual acuity range the next step is to perform the reading tests under artificial lighting conditions with an illuminance of about 500lux on the work place.

[11] This response box has been borrowed from the University Eye Clinic Freiburg, Prof. Michael Bach is acknowledged for his kind cooperation

Figure 5–7: A fisheye picture from the lighting situation in the part 2.

This part includes different phases that are explained in the following.

- **Phase 1 - Reading acuity test**

This phase is to determine the personal reading acuity (reading speed) of the subjects. The flash slides with the highest possible contrast ratio (black text on white background) are exposed on the middle part of monitor with a decreasing exposure time. The exposure time decreases in a logarithmic order in nine successive slides, set equal to 20, 14, 10, 8, 6, 4, 3, 2 and 1 seconds. These exposures make the reading speed from 40 to 800 standard-length word per minute[12]. The subject reads aloud from the exposed slides and the person conducting the experiment marks the unread or incorrectly read words out on the fair copy prepared beforehand (see Appendix D). In general any flash slide has 5 rows and each row has 16 characters, i.e. each slide contains 80 characters. The reading rate measurement of character per minute is equal to the correctly read characters divided by exposure time. Assuming the standard word is 6 character sizes long, the personal reading rate of the subjects is converted to standard-length word per minute. In this phase the minimum exposure time by which the subjects are able to read the whole text correctly is determined to be used in the phase 2 and 4 as the fixed exposure time for the contrast slides.

[12] Concept of standard-length word per minute is a method to express the reading speed introduced by Carver, in which the standard word is assumed to have 6 characters and the reading speed is converted from character per minute to word per minute [41, 16].

- **Phase 2 - Contrast test with positive polarity**

In this phase 18 flash slides with different foreground luminance on white background are successively presented. The text luminance changes based on A-B-B-A order to reduce the effect of fatigue through each trail. The exposure time of the slides is fixed for each subject but can vary from person to person. This is equal to the lowest exposure time determined in phase 1, at which the subject can read the whole text correctly. The reading and monitoring process is the same as phase-1.

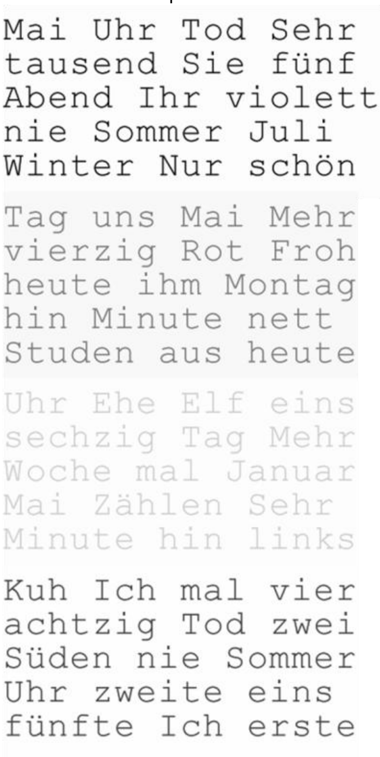


Figure 5–8: An example of A-B-B-A scheme; each text with lower luminance is followed consecutively by two texts with higher luminance and then a text with a lower luminance. This format is repeated throughout the whole contrast test.

- **Phase 3 - Comfort test with positive polarity**

This phase is designed to ask the subjective comfort level under artificial lighting conditions. Similar to the last phase the subjects reads aloud from flash slides. The exposure time here is set high enough in order to give enough time for the subject and exclude the time effect from comfort. The test order is similar to Phase 2 with 18 different slides of different contrast which are exposed in A-B-B-A order. After each slide the subjects are required to state their personal level of comfort by pressing one of the following three options which are labeled on the keyboard.

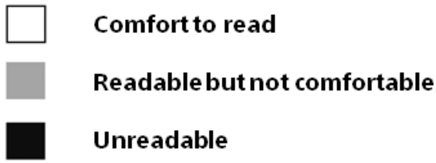


Figure 5–9: Three options of comfort level.

- **Phase 4 - Contrast test with negative polarity**

This phase is exactly identical with Phase 2, but it is implemented with negative text polarity.

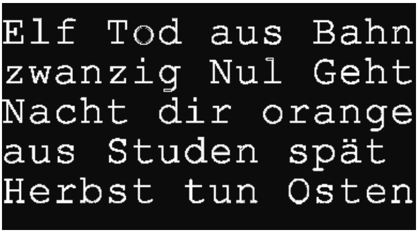


Figure 5–10: Negative text polarity.

- **Phase 5 - Comfort test with negative polarity**

This phase is similar to test phase 3, but is implemented with negative text polarity and after each slide the subjects are asked to state their personal level of comfort by choosing one of the three options illustrated in Figure 5–9.

5.1.2.3 Part 3 - Reading test under daylight condition

In this part of the experiment the venetian blinds and curtains are removed in order to let the natural light into the room. All test phases described in part 2, apart from phase-1, are again being implemented. Phase 1 which is determining the personal reading rate and exposure time is omitted because the personal reading acuity is to be calculated for the highest possible contrast ratio (excluding the effect of light reflection on the monitor). Therefore, in this part the following phases considering the effect of daylight related reflection on the screen are conducted:

- Phase 2: Contrast test with positive polarity
- Phase 3: Comfort test with positive polarity
- Phase 4 Contrast test with negative polarity
- Phase 5 Comfort test with negative polarity

Figure 5–11: Monitor under daylight condition. As visible in this image the direct light from the outside is reflected on to the screen. Even such extreme cases are considered in the experiment to provide a dataset including all possible conditions for evaluation.

5.2 Results

5.2.1 Calculation of final text-contrast

During the reading test the reflection on to the computer screen could change the luminance of text and its background; therefore to calculate the actual value of the text contrast it is necessary to compute the reflection luminance. For this reason the following procedure is implemented:

- In an entirely dark room and by CCD camera, luminance pictures are captured by the monitor with a homogeneous background and from the subjective eye position.
- During the reading tests the monitor is photographed by the CCD camera enclosing a fisheye lens and mounted close to the observer's head position.
- The luminance pictures taken in dark room and under daylight are evaluated in order to derive the luminance of the middle part of the screen (exposure-area of reading-text) after and before reflection (see Figure 5–12):

$$L_r = L_2 - L_1 \tag{5–3}$$

L_r: Luminance of reflection [cd/m^2]
L_2: screen luminance under daylight [cd/m^2]
L_1: screen luminance in a dark room [cd/m^2]

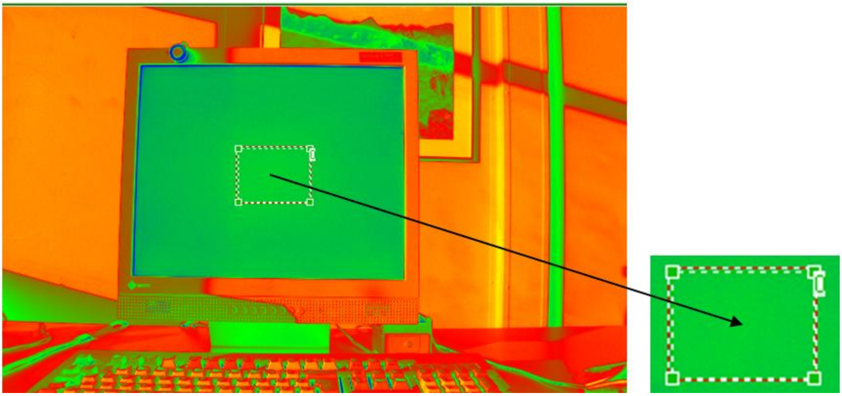


Figure 5–12: Luminance of the middle part of the monitor after and before reflection (in dark room and under daylight) are calculated to derive the reflection luminance on the exposed area during the reading test.

5.2.2 Calculation of average environmental luminance

Average ambient luminance in the visual field is another parameter which is to be evaluated in this study. To monitor the environmental luminance during the experiment a CCD camera is mounted on to a tripod, located close to the subjective head position and directed towards the visual task, is set to automatically capture fisheye pictures every 30 seconds, (see Figure 5–13). To compute the environmental luminance the fisheye pictures are first converted to a RADIANCE picture file format (*.pic) and then the luminance value of all the pixels in the field of view are averaged to achieve the environmental luminance. The respective software of the LMK camera can also be used for deriving the environmental luminance by opening all pictures one by one by the software which according to the great number of pictures would be greatly time consuming. But due to the capabilities of RADIANCE, after converting them to RADIANCE format it is possible to automate the process by writing a script.

Figure 5–13: Fisheye pictures taken automatically every 30 seconds by means of a CCD camera close to subjects head position, these pictures are used to calculate the environmental luminance.

5.2.3 Evaluation of minimum required contrast

5.2.3.1 Minimum contrast for keeping maximum readability

As described earlier each subject conducts a reading acuity test with a high contrast (black text on white background) under artificial light (part2, phase 1) and in this test, the lowest exposure time at which the subject could read the whole text correctly is called "personal time". Personal time is the minimum exposure time at which the subject has her/his maximum reading ability. The personal time is used as a fixed exposure time for phase 2 which is a reading test with 18 different contrasts to clarify which contrast is enough to read the whole text correctly. This test is to determine the minimum contrast by which the subjects could keep their full readability. Thereafter, this concept is titled as "Minimum required contrast for maximum readability". In fact the one important object of this research is evaluating the "Minimum Required Contrast for Maximum Readability". This procedure is clarified in the following flow chart.

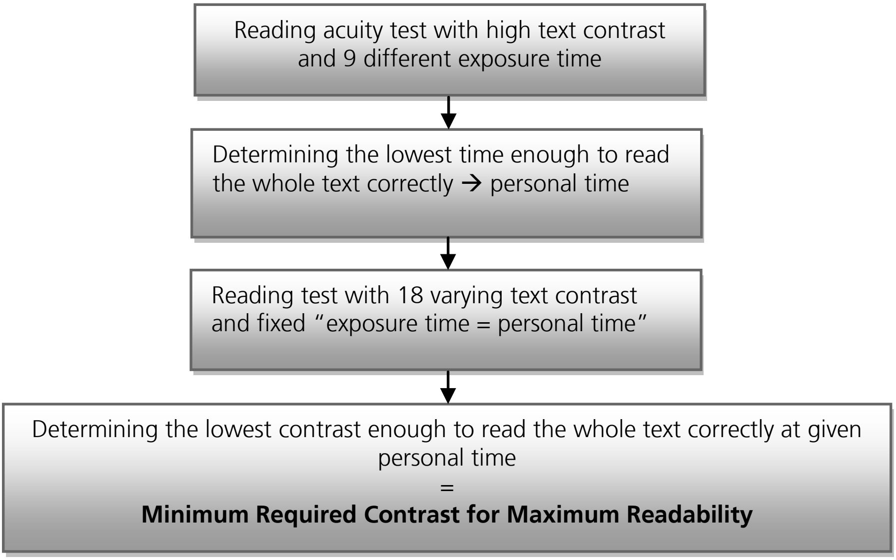


Figure 5–14: Flowchart illustrating the procedure of evaluation the reading test result in order to achieve the value of minimum required contrast for maximum readability.

5.2.3.2 Minimum contrast necessary for comfort reading

In the phase 3 and 5 which are reading tests with a high exposure time and different contrast the subjects are required to state their comfort level after each slide. The exposure time is set up to a high value in order to exclude the effect of the time shortage in comfort rating.

In this phase subjects are confronted with three comfort options to choose, i.e. "comfort to read", "readable but not comfortable" and "unreadable". The purpose is to evaluate the "lowest text contrast stated as comfort to read". Thereafter this concept is entitled as "Minimum Required Contrast for Comfort Reading".

In Table 5-2 the contributions of exposure time, contrast and comfort to three different test phases and the outcome of each step are illustrated.

Table 5-2: The influence of exposure time, contrast and comfort in three test steps and final outcome of these tests.

	Exposure time	**Contrast**	**Comfort level**	**Outcome**
Reading acuity test	variable	Fixed : highest possible	-	Personal reading rate (maximum readability with high contrast)
Contrast test	Fixed : determined in previous step	Variable	-	Minimum required contrast for maximum readability
Comfort test	Fixed: high	Variable	Three levels	Minimum required contrast for comfort reading

5.2.4 Evaluation of the data

In order to evaluate whether the existing standard models for "Minimum Required Contrast" are fitting to the subjective results of the conducted user assessments study or not a correlation study is performed. For this purpose the subjective results are split into two categories comprised of two separate defined contrast concepts of:

- Minimum required contrast for maximum readability
- Minimum required contrast for comfort reading

The most important model which is to be evaluated and be compared with the observational data in this study is the latest standard model for minimum contrast (from ISO-9241-303 which was explained in the part *2.3-Veiling glare"*, equation 2–11) as this model is an up-to-date standard suggestion. Moreover, Poynter model for contrast requirement for display legibility (explained in the part *2.3-Veiling glare"*, equations 2–12 to 2–19) is also to be evaluated against the above mentioned observational dataset.

It should also be mentioned that the estimated contrast requirement based on ISO-standard-model is a function of the age of the observers and the low-state luminance which in case of positive polarity is the text-luminance and in case of negative polarity is the background-luminance (see equation 2–11) and Table 2-1). The estimated contrast requirement based on the Poynter-model is a function of the letter size (equations 2–14 and 2–15), background luminance of display image (equation 2–16), age of observers (equation 2–17) and glare (equation 2–19). In order to compute the required veiling luminance to calculate the glare multiplier of Poynter-model (equation 2–19 and 2–20), a RADIANCE-based computer tool called "EVALGLARE" is used which obtains the fisheye pictures (taken during the tests, see Figure 5–13) and detects the glare sources in the field of view in order to calculate the veiling luminance [80]. As the reading texts within this study have no color-contrast the multiplier for color consequently (equation 2–18) is not taken into account for computing the contrast requirement based on the Poynter-model.

After categorizing the subjective results each category is compared with both the ISO-standard model and the Poynter-model for a minimum required contrast to verify whether the existing models correlate with the subjective results or not. Table 5-3 and Table 5-4 show the results of the Pearson correlation performed between the estimated-data by existing models and the observed-data for both concepts of contrast-requirements (maximum readability and comfort reading). Each contrast-concept includes the achieved results with both positive and negative text polarities.

Table 5-3: Result of Pearson correlation study between the observed data and estimated data by ISO-standard model.

ISO-model	Min contrast for maximum readability	Min contrast for comfort reading
Pearson Coefficient	0.194	0.512
Significance level (p-value)	0.058	<0.01

Table 5-4: Result of Pearson correlation study between the observed data and estimated data by Poynter-model.

Poynter-model	Min contrast for maximum readability	Min contrast for comfort reading
Pearson Coefficient	0.483	0.596
Significance level (p-value)	<0.01	<0.01

In the following figures there are two diagrams illustrating a comparison between the data distributions of the observed and estimated datasets by the ISO-standard model in both categories of "minimum contrast for maximum readability" and "minimum contrast for comfort reading" with both polarities. The datasets are sorted by age to visualize the effect of age as observed in the subjective tests and also as predicted by the standard model.

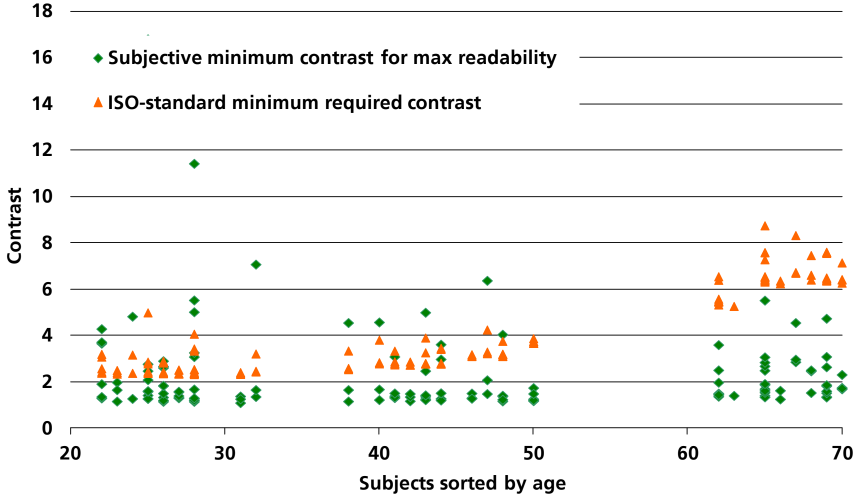


Figure 5–15: Comparison between the subjective perceptions of minimum contrast for maximum readability and the minimum required contrast estimated by the standard model.

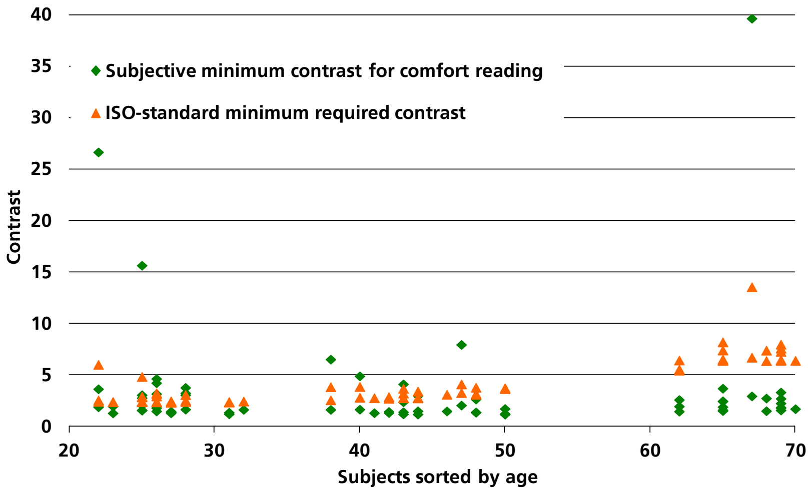


Figure 5–16: Comparison between the subjective perceptions of minimum contrast for comfort reading and the minimum required contrast estimated by the standard model.

5.3 Summary and discussion

Different reading tests with varying exposure times or contrasts and under different conditions are performed within the scope of this chapter to evaluate the following concepts:

- The minimum contrast for a good readability:
    - Relationship between the existing contrast models and the subjective results of this concept.
- The minimum contrast for a comfort reading:
    - Relationship between the existing contrast models and the subjective results of this concept.

The results of this study can be summarized and discussed as the following:

- The ISO-standard model for minimum contrast (equation 2–11) has a very poor correlation factor of 19% with the observed data from the reading test with a level of significance of about 0.06 which is higher than the permitted minimum limit for a correlation (0.05). This means that according to this study the ISO-standard cannot predict the minimum required contrast for good legibility.
- The ISO- standard model also has a relative poor correlation with the observed data from the contrast test with a correlation coefficient of 51%. Therefore, according to this experiment the ISO-standard model cannot conveniently predict the minimum required contrast for comfortable reading.
- The suggested model by Poynter (equations 2–12 to 2–19) has a poor correlation with both the observed data from the reading test and the contrast test with Pearson coefficients of 48% and 59% respectively. Hence, based on the current study the Poynter model is not a proper indicator for minimum required contrast - neither for good legibility nor for comfortable reading.
- The difference between the distributions of predicted data by the ISO-standard model and the observed data increases by increasing the age of subjects. This indicates that the age effect on the observers' contrast perception/preference in the standard model is overestimated. A similar conclusion was deduced from the study performed in chapter-3 on the contrast threshold model ("*3- Experimental study to evaluate existing contrast threshold*").

These evaluation results show the necessity to improve the standard model or to develop a new model which fits better to the subjective perceptions and ratings of contrast by working with a computer screen. In the next chapter the evaluation process to develop a new model for minimum required contrast is explained.

6 MRC Model development

6.1 Method

After concluding that the standard model of minimum required contrast does not fit to the subjective perceptions and ratings of contrast by conducting the reading tests in chapter-5, the next step is to develop a new model which fits better to the subjective estimations. This development is the main focus of this chapter. Thereafter, in this research the concept of "Minimum Required Contrast" is named with the abbreviation of MRC and the model to be developed in this chapter is also entitled "MRC model".

6.1.1 Project methodology

In this chapter the process of developing a new MRC model based on the results of chapter-5 is described. The model is developed using the following four observational datasets with a total number of 168 observations:

- **Dataset 1:** "Minimum contrast for maximum readability from the test phase "contrast test with positive polarity".
- **Dataset 2:** "Minimum contrast stated as comfort to read from the test phase "comfort test with positive polarity".
- **Dataset 3:** "Minimum contrast for maximum readability from the test phase "contrast test with negative polarity".
- **Dataset4:** "Minimum contrast stated as comfort to read from the test phase "comfort test with negative polarity".

Thereafter, the mentioned categories of datasets are termed as dataset 1 to 4.

6.1.2 Experimental Procedure

The procedure of developing the model can be summarized in the following steps:

- Proposing a hypothesis for the model structure
- Determination of the age factor
- Determination of the constants and exponents

6.1.2.1 Hypothesis of the model structure

The existing standard model for minimum required contrast is a function of age and low state luminance[13] [36]. In fact the structure of the existing standard

[13] As mentioned earlier by reading a text the low state luminance or L_L is the smaller luminance e.g. the by reading a black text on a white background the L_L is the luminance of the text and the L_H (high state luminance) is the luminance of background.

model (equation 2–11) and the former standard model stated in "ISO 13406-2" [27] (equation 2–7) is similar and is based on the following formulation:

$$CR_{\min} = K_{age} \cdot (a + \frac{b}{L_L{}^{c}}) \tag{6–1}$$

CR_{min}: minimum required contrast for performing a visual task on the visual display
K_{age}: age multiplier
L_L: low state luminance
c: weighting exponent of low state luminance

For computer based tasks, the adaptation level of the eye is not only affected by the task itself. The adaptation level is also influenced by the environmental luminance – especially for daylight spaces. Therefore, it is probable that the environmental luminance also influences the minimum required contrast and is added to the model structure to be tested. Environmental luminance (L_E) is in fact the average luminance of the entire field of view. This value has been computed via the luminance pictures captured by CCD camera using the fisheye lens during the experiments, as described in the chapter-5.

Whether the contrast perception results are a function of age or not it is not easy to foretell from the primary observations review. In fact the results seem to be more influenced by other two factors (L_L and L_E) compared to the factor of age. But as age is typically a factor on visual related issues and it also appeared to be a parameter in the evaluations performed in chapter-4 on the contrast threshold model (see Figure 4–13 and Figure 4–14), therefore it is taken into account in the model structure that is to be tested. Hence the new model would have the following hypothetical structure which is the function of three variables, i.e. age, low state luminance and environmental luminance:

$$MRC = K_{age} \cdot \left[a + b \cdot \left(\frac{L_E{}^{c}}{L_L{}^{d}} \right) \right] \tag{6–2}$$

MRC: new minimum required contrast
K_{age}: age multiplier
L_E: Environmental luminance
L_L: low state luminance
c,d: weighting exponents

In this study there are four different datasets of subjective results including minimum contrast for "maximum readability" and "comfort reading" with "positive polarity" and "negative polarity". People usually need a higher text contrast ratio for performing a reading task comfortably versus performing a reading task correctly. That means that the minimum required contrast for comfort reading is most likely higher than minimum contrast for maximum readability (this is also evident when making a quick review of the observed data). For this reason an extra factor is assumed for comfort in the model. The same argument is valid for the polarity. According to the subjective results of the current study performing reading task with negative polarity requires higher contrast. Therefore a polarity index is also assumed in the model to be tested. Consequently the hypothetical format of the model is extended to the following structure:

$$MRC' = \frac{MRC}{K_{age}} = a_1 + a_2 \cdot CI + a_3 \cdot PI + b \cdot \left(\frac{L_E{}^c}{L_L{}^d} \right) \qquad (6\text{–}3)$$

MRC’: minimum required contrast for age under 30
MRC: minimum required contrast for all ages

CI: Comfort index =
- 0 for maximum readability
- 1 for comfort reading

PI: Polarity index =
- 0 for positive polarity
- 1 for negative polarity

Applying the age factor (K_{age}) on the left side of the equation is to prevent the inconvenient multiplication of K_{age} by CI and PI. By applying K_{age} on the right side it would be multiplied by comfort and polarity indices (CI and PI) just when they are equal to one, i.e. when the model is used for comfort reading and negative reading.

6.1.2.2 Determining the age factor

After defining the hypothetical format of the model based on the standard model and extra parameters that are assumed to have influence on the contrast perceptions the next step is defining the age factor. The age multipliers used in the standard model for minimum contrast are illustrated in Table 2-1. As visible in this table in the standard model age has been considered to have a strong influence on the calculation of the required minimum contrast and it is changing from 1 for the age of 20-25 to 2.66 for the age of 65. It means that the estimated minimum contrast for a person of age 65 years would be 2.66 times higher than the estimated minimum contrast for a 20 years old person for the same low state luminance. As described in chapter-5, the user assessment study has been conducted in three different age groups i.e. groups of 20-30, 40-50 and 60-70 years of age. A review of the achieved results clarifies that the age of the test person is not as effective as stated in the ISO-standard model. This can be well observed in Figure 6–1. This diagram shows that the estimated values by the standard model for the older age groups are obviously higher than their real contrast perceptions.

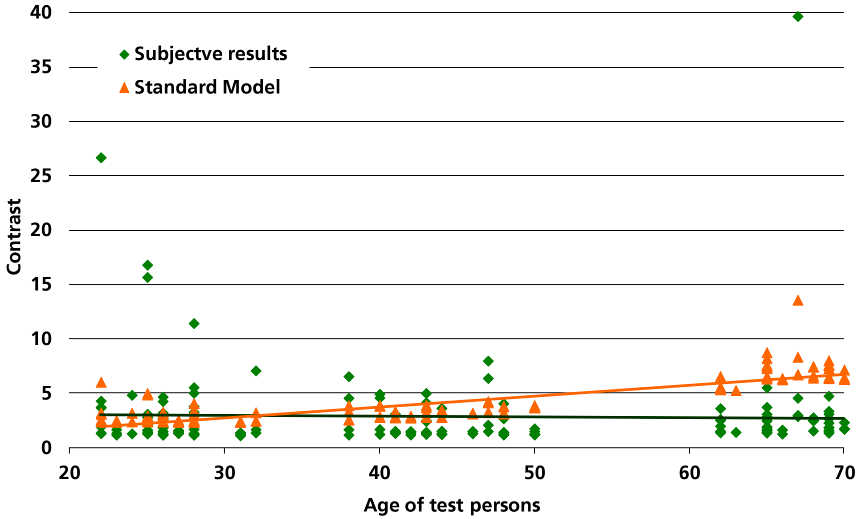


Figure 6–1: Diagram shows the relationship between age and both subjective contrast perceptions and estimated values by standard model (of all datasets together). The comparison between both trend-lines demonstrates that the standard model overestimates the age effect on contrast perception. The trend-line of observed data (green line) shows that the influence of age in contrast perception is in fact minimal.

Definition of the age factor is one of the first steps in developing the model. The next three options for defining age factors are conceivable:

- Discarding the age effect according to Figure 6–1 in which this effect is minimal.
- Considering unrelated values as an age factor for different age intervals (similar to Table 2-1).
- Considering the age factor as a linear function of the age-variable.

Since every data point in the dataset is a function of two other variables other than age, thereby determining the age effect without considering other variables is not possible. Therefore, it is considered to define the age factor simultaneously with other variables in the explained procedure. This procedure is performed separately for each of the four datasets using the Pearson correlation.

Primary evaluations based on the Pearson correlation of all four datasets show that consideration of a low-value age-factor for the age over 30 would lead to a better correlation compared to discarding the age factor altogether. In the results from the age group under 30 (20-30 years old), age has no influence on the contrast perception and considering no age factor (K_{age}=1) in this age group shows a better correlation.

The next step is to decide between independent or functional values. As mentioned before the tested age groups are in three ranges of 20-30, 40-50 and 60-70. Considering the existing gaps in the range of 30-40 and 50-60, it seems more reasonable to have a functional age factor instead of unrelated values for various intervals. Unrelated values could lead to more inaccuracy due to the missing intervals.

For developing an appropriate function for age factor the following procedure is implemented:

- K_{age} for age > 30 is considered to be a linear function of age:

$$age \leq 30 \Rightarrow K_{age} = 1$$
$$age > 30 \Rightarrow K_{age} = a \cdot age + b \qquad (6\text{–}4)$$

- For deriving a, b values, different assumptions for K_{age} of 70 years old (maximum measured range) are made.
- All age multipliers are computed based on various assumptions of K_{70}. The computed multipliers based on each assumption are evaluated for all four datasets and compared together (these evaluations are based on the Pearson correlation).
- Between different tested values the following values show a good correlation with all four observed datasets and are accepted as age factors:

$$age \leq 30 \Rightarrow K_{age} = 1$$
$$age > 30 \Rightarrow K_{age} = age \cdot 0.0025 + 0.925 \qquad (6\text{–}5)$$

  This is based on the following assumption:

$$age = 70 \Rightarrow K_{age} = 1.1$$

Figure 6–2 illustrates the diagram of the developed age multiplier (K_{age}).

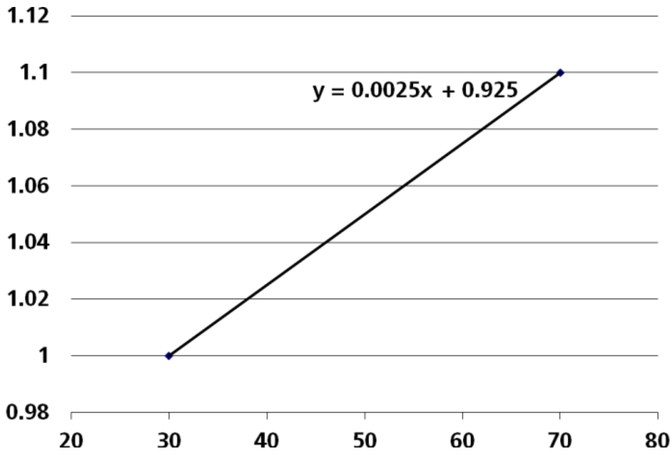


Figure 6–2: Diagram for the age factor over 30.

6.1.2.3 Defining constants and exponents by non-linear regression

There are two different options for deriving the exponents and constants of the model stated in equation 6–3:

- Separate evaluation of each of the four datasets by linear regression and the Pearson correlation for deriving the constants and exponents:
    - Starting the evaluation from the dataset 1 i.e. "positive polarity and maximum readability" (as this category is more likely to be confronted in a real office situation it is considered as the most important one) and defining the common parameters of "a_1","b","c" and "d" for this table.
    - Continuing the evaluations using dataset 2 i.e. "positive polarity and comfort reading", to define the comfort parameter "a_2".
    - Going further using datasets 3, 4 i.e. observations with negative polarity to determine the polarity parameter "a_3".
- Merging the four datasets and perform the evaluation for the whole dataset together.

The evaluations are based on the first option mentioned above. However, deriving the parameters for one dataset results in the difficulty of fitting the parameters to other datasets. If compromises are made when matching the parameters to other datasets inaccuracies can arise in all of them. This is especially evident when computing the value of rRMSE (relative root means square error). That means this method would bring about high values of rRMSE for all datasets. Hence, because of this difficulty the decision was made to apply the second option for this evaluation. After merging the four datasets it is not possible anymore to determine the parameters by means of linear regression and the Pearson correlation in an accurate manner. Therefore, it was decided to apply a non-linear regression method for developing the model and determining the parameters mentioned in equation 6–3. Nonlinear regression is a type of regression analysis to model the observational data by a function of one or more independent variables, which is a non-linear mixture of various parameters. The model which is to be determined by nonlinear regression analysis in this study (stated in equation 6–3) has five parameters - a_2, a_3, b, c and d, as well as five independent variables i.e. K_{age}, CI, PI, L_E and L_L.

As K_{age} was developed in the previous part in this part of analysis it is considered as an independent variable instead of a parameter. The value of a_1 is also considered as a constant value and equal to 1.1; the reasons for this consideration are[14]:

- To prevent any potential MRC estimation less than one which would be an unrealistic estimation of contrast ratio;
- The minimum value of contrast ratio (subjective contrast perception for good readability) within the entire observational data is close to 1.1.

Therefore the model to be fitted by non linear regression is as following:

$$\frac{MRC}{K_{age}} = 1.1 + a_2 \cdot CI + a_3 \cdot PI + b \cdot \left(\frac{L_E{}^c}{L_L{}^d} \right) \qquad (6\text{–}6)$$

After assessing different possibilities to facilitate conduction of non-linear regression, a computer based tool called "CurveFitter" [46, 57] is applied for this reason which seems to be a convenient choice for this study.

The program "CurveFitter" has a graphical user interface to import the list of independent variables and dependent variables (observational data), the formulation of the model and the initial guesses of parameters to start with. The output would be the best fitted parameters and the results (estimated data by means of fitted model).

[14] Apart from the mentioned reason and to confirm the reliability of the considered quantity of 1.1, non-linear regression was performed several times with different a_1 quantities close to 1, and 1.1 showed to be a good fit for this model.

The model-parameters derived by implementing the non linear regression via CurveFitter are listed as the following:

- a_2= 0.33
- a_3= 0.37
- b=16.2
- c= 0.41
- d= 1.54

By replacing the achieved parameter in the model, the final proposed MRC model reads:

$$\frac{MRC}{K_{age}} = 1.1 + 0.33 \cdot CF + 0.37 \cdot PF + 16.2 \cdot \left(\frac{L_E^{\ 0.41}}{L_L^{\ 1.54}} \right) \quad (6–7)$$

This model is a broad-spectrum model which covers both comfort categories (maximum readability and comfort to read) on the one hand and both polarity categories (positive and negative polarity) on the other hand, while in the existing standard model no separate factor for comfort and polarity has been considered.

6.2 Results

After deriving the parameters through non-linear regression, other statistical analyses are conducted in order to verify the precision of the model. These analyses are summarized in the following list:

- The Pearson Correlation analysis between the new model and subjective results to verify the consistency of the model.
- Relative root mean square error (rRMSE) analysis to confirm the precision of the model.
- Re-sampling and boot-strapping analysis for the same data set, in order to make sure that the correlation has not been done randomly.
- Intra-class correlation for the data to check the reliability of the model.
- Testing the developed model against the dataset from another user assessment study included the task of contrast perception (described experiment in chapter 3).
- Testing the robustness of the MRC model with regard to the extreme values (outliers).

6.2.1 Pearson correlation

In this part a Pearson correlation analysis is implemented between the observed data and the estimated data by the MRC model in order to confirm the reliability of the parameter estimated by non-linear regression analysis. In Table 6-1 the results of the implemented Pearson correlation between the subjective results and both standard model and new MRC are illustrated[15]. As demonstrated in this table the difference between the standard model and the new model is considerable and the standard model shows very low correlation with subjective results achieved in this study.

Table 6-1: Pearson coefficients achieved from the correlation study between the observed data and both new MRC and ISO-standard model.

	Pearson Coefficient	**Significance level (p-value)**
ISO-standard model	38.3%	<0.01
New MRC model	98.1%	<0.01

The diagram in Figure 6–3 clarifies the significant difference between the new developed MRC and standard model in correlating with the observational dataset and the quantity of the least square in both cases. “Least square” value is another interpretation of correlation and is defined as the square value of Pearson correlation coefficient.

[15] Table 5-3 shows the Pearson correlation results between the observed data and predicted data by ISO standard model achieved for the same dataset but divided into two parts consists of the data of “minimum contrast for maximum readability” and the data of “minimum contrast for comfort reading”. But the illustrated Pearson coefficient in Table 6-1 has been achieved within the whole dataset. This is the reason for different coefficients in these two tables.

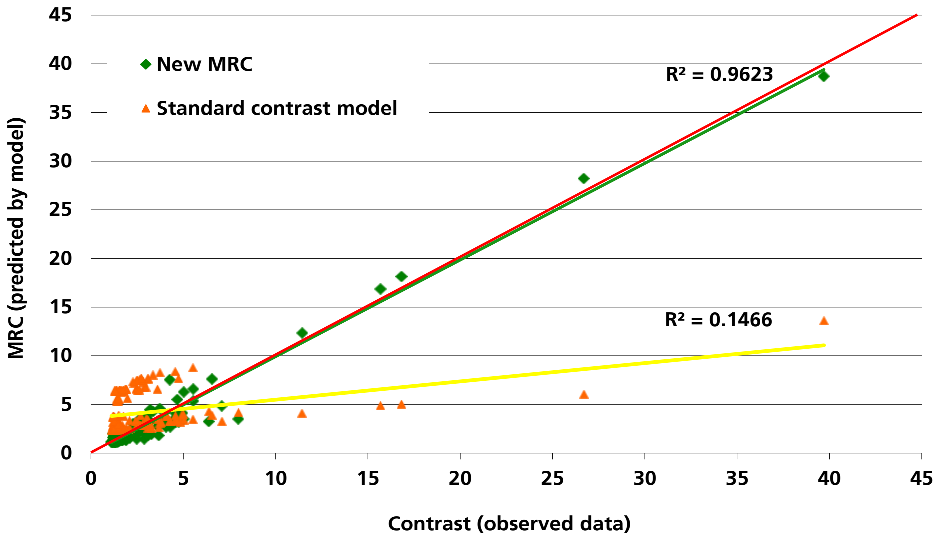


Figure 6–3: Diagram demonstrates a comparison of relationships between the observed data and both standard and new developed MRC. The red line represents the ideal situation, the green line is the trend line of the predicted values by the new model, and the yellowish line is the trend line of the predicted values by the standard model. As visible the trend line of the predicted data by new MRC model is very close to the ideal situation.

6.2.2 Relative root mean square error (rRMSE) analysis

Another method to confirm the precision of the new model is performing the root mean square error analysis. The root mean square error (RMSE) is a measure to indicate the differences between predicted data by a model and the observed data obtained from the subjective study. RMSE is a good measure to show the precision of the model. In this study the relative root mean square error (rRMSE) is used instead of RMSE, which is formulated as:

$$rRMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{CR_i - MRC_i}{CR_i}\right)^2} \qquad (6\text{–}8)$$

N: number of observations
CR: actual contrast ratio, observed data
MRC: contrast requirement estimated by the model

The results of this evaluation which are multiplied by 100 and stated in percent (%) are demonstrated in Table 6-2. The lower the rRMSE would be, the better a model predicts the observed data. These results show that the ISO standard model predicts the observed data with a relative difference of 149% while this difference between the predicted data by the new model and observed data is 22.8%.

Table 6-2: results of rRMSE analysis performed for both new MRC model and standard model relative to observations.

	rRMSE [%]
ISO-standard model	149%
New MRC model	22.8%

6.2.3 Boot-strapping

To ensure that the achieved correlation is not random a bootstrapping analysis is performed. Bootstrapping is a re-sampling method and can be implemented by constructing a number of re-samples from an observed dataset and of equal size to the observed dataset. Each resample is made by a random sampling from the original dataset. [16]. As the new resample-datasets are made totally at random a data point can occur several times or can be omitted in the new resample. The estimator which has been tested in this analysis is the Pearson Coefficient. In Table 6-3, the results of boot-strapping with the number of 10000 bootstrap samples are illustrated. This table includes the number of bootstrap samples (valid iteration), the mean of 10000 coefficient values averaged through 10000 bootstrap samples, their variance, and the lower and upper bounds of the confidence limit.

Table 6-3: Results of bootstrapping analysis. "Mean" is the mean value of the Pearson coefficients of all 10000 resamples. "Lower CL" is the lower bound of confidence limit and "Upper CL" is the upper bound of confidence limit.

	Mean	Variance	Lower CL	Upper CL	Valid iterations
Bootstrapping analysis	0.972	0.000636	0.92	0.99	10000

As is to be seen the average value of Pearson coefficient obtained from the 10000 resamples is very high and is between 92% and 99%. This is an indicator that the achieved correlation has not been random and has a high measure of accuracy.

[16] In this study Bootstrapping has been implemented by means of tool called PopTools which is an add-in of Microsoft Excel (97, 2000 or XP): http://sunsite.univie.ac.at/spreadsite/poptools

6.2.4 Intra-Class Correlation

By performing a Pearson correlation between two rates the high coefficient definitely shows the agreement of judges on ordering but not necessarily their agreement in respect to magnitude [33]. For example, as stated in Table 6-1, the Pearson coefficient obtained from the correlation study between the estimated data by the new model and the observational data is equal to 98% and by multiplying the estimated data by 10 (or any other value) the coefficient won't be changed (=98%). This is due to the reality that Pearson correlation shows the correlation of two rates in respect to their relative and not their absolute magnitudes. To prove that both datasets are in correlation also with respect to magnitude[17] an Intra-Class correlation analysis is implemented. A high value of Intra-Class correlation coefficient (ICC) would be an index of reliability of the ratings. In the following table the results of Intra-Class correlation between all the observation datasets and the developed MRC is demonstrated. This statistical analysis is implemented by means of a computer based program called SPSS (Statistical Package for the Social Sciences).

Table 6-4: Results of Intra-Class correlation implemented between the observed data and estimated data by new developed MRC model.

	Intra-Class Correlation	**95% Confidence Interval**	
		Lower Bound	Upper Bound
Single Measures	0.981	0.974	0.986
Average Measures	0.990	0.987	0.993

As illustrated in Table 6-4 the derived coefficients by intra-class correlation are also high which is an indicator of the reliability of the new developed model to predict the observed data in respect to both order and magnitude.

6.2.5 Testing the developed model against other datasets

To assess the validity of the new developed MRC model it was decided to test the model against another dataset. For this reason the subjective results from another experimental user assessment study are applied. This study is the user assessment study (explained comprehensively in the chapter-4, "*Experimental study to evaluate existing contrast threshold*"). As described the task in the experiment has been the identification of the Landolt ring gaps while

[17] The rRMSE analysis is also a method which demonstrates the reliability of the estimator in respect of magnitude. Nevertheless, an ICC analysis is also performed to confirm the reliability. Implementing of ICC was recommended by a statistical advisor.

performing the respective contrast tests. In general, the number of available identified cases is 17069 obtained from 640 trials from which, 8856 records are from outlook series, 3722 records from brightness series, and 4491 records from age series (refer to chapter-4, for more information about series). These records have been obtained from 72 test persons. To evaluate all these results the following procedure applies:

- Determine the minimum identified contrast in any trial (throughout the whole 30 cases in each trial).
- Determine the minimum identified contrast by each test person throughout all trials (by comparing the minimum identified contrasts in all performed trials by each test person).
- Perform a correlation study between the personal minimum identified contrast and both new developed model and standard model.

However, it should be mentioned that the MRC model has been developed for a reading task which requires a higher contrast than an identifying task. Furthermore, for developing the MRC model, the dataset of comfort reading has been also taken into account; whereas with the Landolt ring identification task the results are representing just the identification ability of the trial persons and not their comfort status. Accordingly it is not expected that the correlation between the new MRC model and the results of Landolt C identification would be as high as the achieved correlation for the reading task and the MRC model. Nevertheless, as reading and identifying have the same concept (reading is a higher level of identifying) it is expected that between the developed model for reading and the dataset of identification test there would be a correlation.

A Pearson correlation analysis is implemented between the observational data of Landolt ring study and both the new MRC and the ISO-standard model. As illustrated in Table 6-4, the observed data from the Landolt-ring test and estimated data by new MRC model correlate with a Pearson coefficient of 73%. This is a higher correlation compared to the achieved correlation between the observed and estimated data by the ISO-standard model with a coefficient of 49%. This difference is demonstrated also in Figure 6–4, which is a scatter diagram representing the relationship between the observed data (minimum identified contrast) and estimated data by both the new MRC and the ISO-standard model. As visible in this diagram the scattering of the estimated data by the ISO-standard model is very high which is mostly due to the overestimated age factor in this model.

Table 6-5: Pearson coefficient between the observed data of Landolt ring test and both the new MRC and the ISO-standard model.

	Pearson Coefficient	Significance
ISO-standard model	49%	<0.01
New MRC model	73%	<0.01

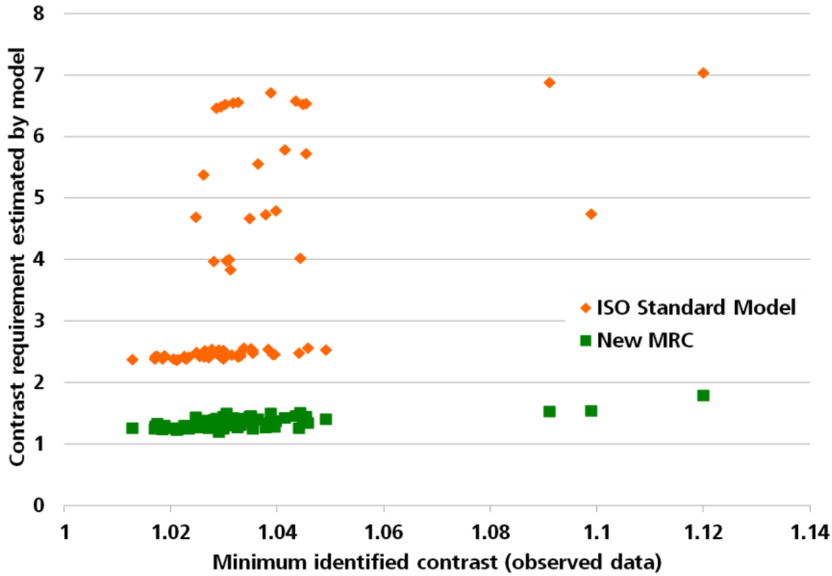


Figure 6–4: Relationship between the minimum identified contrast achieved from subjective test and estimated minimum contrast by both the standard model and new developed model.

6.2.6 Robustness of the model to extreme values

In the dataset applicable to the development of the MRC model there are few data points with higher rates relative to the majority of data points. By considering these few observations as extreme values the question is raised as to whether the achieved correlation is robust to extreme values or not. It shall be found out whether the correlation is influenced by these high values and whether the model is still correlative when considering these values or not. The mentioned data points are illustrated in Figure 6–5.

Discarding these data points and not taking them into account by developing the MRC model would have not been a solution as it is intended to develop a model for all situations including the situation in which the minimum required contrast to read would be high. In fact the circumstances which result in very high minimum contrast are the most critical ones and should definitely be taken into consideration when developing the model. However, verifying whether or not the model is robust to the extreme values and the correlation is not caused by these values; they are removed from the dataset and Pearson correlation coefficient (R) and square of correlation coefficient (R^2) are computed for dataset with and without extreme values. Figure 6–6 and Table 6-6 demonstrate the results from this study.

Table 6-6: Computed relative root mean square error (rRMSE) for the new MRC model based on a dataset without extreme values.

	R (correlation coefficient)	**R^2**
Dataset without extreme values	0.98	0.96
Complete dataset	0.82	0.67

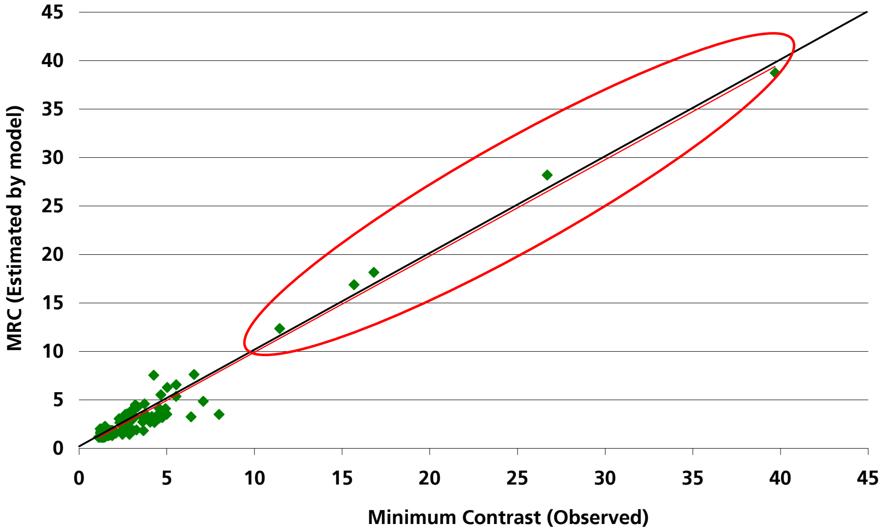


Figure 6–5: Relationship between the observed data and estimated data by the developed model. The five distinguished data points would be considered as extreme values and be removed from the dataset to ensure that without these high values the model is still reliable.

Figure 6–6: Relationship between estimations by the new MRC model and the observation data excluding extreme values. The red line is the trend-line of the data points and the black line is the optimum condition.

As visible in Table 6-6 the computed values of “correlation coefficient” and “R^2” for the dataset without extreme values are not as high as the obtained values for the whole dataset but they are still in an acceptable range. This indicates that the developed model is nevertheless correlative with the observational data.

6.3 Conclusion and outlook

In this chapter based on the results gained from the user assessment study (explained in chapter-5) and the standard model of “minimum required contrast” a new model titled “MRC model” has been developed. The developed model covers both positive and negative text polarities and also both reading and comfort criteria i.e. maximum readability and comfort reading. The parameters are determined by conduction of a non-linear regression analysis. The Pearson coefficient, relative root mean square error, Intra-Class coefficient and bootstrapping analysis are all performed on the developed model to verify its reliability and precision - all the outcomes are correlative. Furthermore, by testing the developed model against a new dataset from another user assessment study, a correlation is to be seen which is considered as kind of validation.

There are few observations with contrast preference of higher than 10 in the dataset (5 data). The high measures of minimum contrast usually happen when the low state luminance is very low. For instance, by working in a very dark room the reflection on the screen is very low and therefore the initial low state luminance of a black text (about 1cd/m^2) changes slightly; this results in a high amount of minimum required contrast. In the underlying user assessment study of the model development the phenomenon of very low state luminance occurs just in a few cases as the tests are commonly performed under daylight conditions. This is the reason that there are such little data with very high required contrast in the available dataset. Consequently, the outlook for the further improvements in this regard would be performing an additional user assessment test under specific conditions (e.g. dark room conditions) to deliver more cases with a high value of minimum required contrast.

Although this model has been developed for the onscreen visual task in office spaces the main concept is still the contrast requirement for a good and comfort recognition, therefore it is assumed that the model could work for many other applications than have been tested. For example, it can be applied for controlling the legibility of displays in public places, cars and other vehicles or machines. Additional assessments are needed for each application in order to confirm the consistency of the model for that particular purpose.

The results of this chapter can be summarized as:

- According to the conducted evaluation in all age groups, the age influence on subjective contrast preference is significantly less than the considered measure in the ISO-standard model.
- As visible in equation 6–7, the developed model is a function of age, low-state luminance and average ambient luminance (of the whole view field). The effect of low-state luminance is higher than other factors, which indicates that the most important phenomenon in the amount of required contrast is the lower luminance value in the visual task (display image).
- Although the MRC model has been developed for all values of low-state luminance (L_L) according to common ambient brightness in this study (daylight situation), there are few observations with very low value of L_L and thus there is little data in the dataset with a very high contrast requirement.

7 Computer based model for evaluating veiling glare

7.1 Measurements and modeling of a LCD monitor

7.1.1 Introduction

One important task in this research study is performing the accurate lighting simulations based on the real optical behavior of the computer screen. The main simulation program which is applied for lighting simulations within this research work is the RADIANCE program [75]. To conduct an accurate simulation with RADIANCE it is necessary to have a precisely modeled monitor with exact reflection distribution characteristics. To derive the reflection characteristics of a visual display some measurements are made within this study by means of a device called gonio-photometer which delivers the BRDF (bidirectional reflectance distribution function) values of the monitor surface. Based on the measured data a material model is developed for application within the simulations. The display type which is measured and simulated in this study is an LCD type “EIZO FlexScan L56” which is the same display type used for all of the described experimental studies in this research. Finally, in this chapter a comparative study is implemented between the new developed simulation-model of the visual display and two other pre-developed simulation-models of the same display-type. Two other models were provided to the author from other resources and were measured by other measurement techniques. The aim of the comparison is to study the differences between a screen-model based on BRDF measurements and other models based on simpler measurements, in respect to contrast evaluation.

7.1.2 Measurements

Two measurement procedures by means of two measurement devices are conducted within the framework of this Ph.D. study. The reflection behavior of the visual display is measured by means of a gonio-photometer device in order to derive angle dependent reflection characteristics or BRDF (bidirectional reflectance distribution function) of the screen. Descriptions about the gonio-photometer used for this purpose, BRDF concept, and the measuring procedure are available in Appendix E.

After measuring the reflection characteristics of the screen, another measurement is made by means of a device called “integrating sphere” to obtain normal-hemispherical and normal-diffuse reflectance in order to confirm the results of gonio-photometer. Descriptions about the integrating sphere are available in Appendix F.

The illustrations in Figure 7–1 and Figure 7–2 are 3D-visualizations of the measured reflectance data (BRDF values) at different altitudes and azimuth angles of incident light (see Appendix E). Each data point on these 3D-curves is representative of a measured BRDF value by a gonio-photometer. These curves demonstrate the reflectance distribution characteristics of the visual display. The visualizations are made by means of a computer tool called "Mountain"[18] which is a visualization tool for BRDF data.

As illustrated in Figure 7–2, the reflectance characteristics do not change by changing the azimuth angle of the incident light. But it is very much dependent on the altitude angle of incidence. The higher altitude angel of incident beam cause higher specular reflection. These illustrations are the generated combinations of variant BRDF curves which have been composed in one image to facilitate a comparison. In reality at each incident angle the measured data includes the reflection curve at specular and close to specular angle, and the homogeneous ground representing the diffuse reflections for all other angles.

[18] This tool has been developed originally by Peter Apian-Bennwitz and was later modified for further usages under Linux operating system by Christian Reetz.

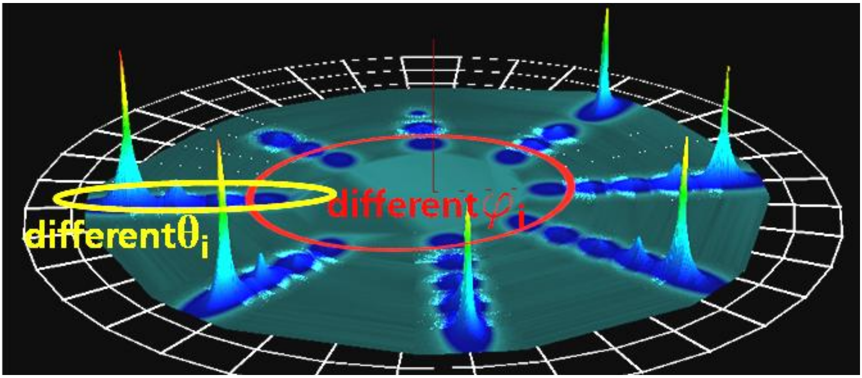


Figure 7–1: Reflectance distribution curves (BRDF values) of the measured monitor surface at different directions of incident light (θ_i, φ_i). Here the reflection curves of the different incident angles are mapped on to one image to facilitate a comparison. The reflection property of the screen material does not change by changing the azimuth angles of incident light or φ_i (see the red highlight on the diagram), but it is very much dependent on the altitude angle of incident light or θ_i (see the yellow highlight on the diagram).[19] The BRDF measurements are performed for θi altering from 30° to 70°. Reflection measurements for lower and higher incident angles are not possible due to the technical restriction of the device [51].

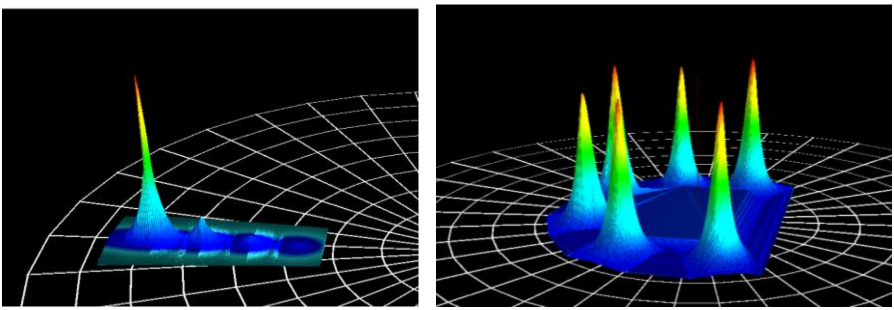


Figure 7–2: Left: measured BRDF for the incident lights with azimuth angle of 0°(φ_i =0°) and different altitude angles. All reflectances are mapped into one image. Right: measured BRDF for the incident lights with altitude angle of 30° (θ_i =30°) and different azimuth angles. All reflections are mapped into one image.[20]

[19] The missing measured curves at some directions of the incident light are due to the measurement restriction of the used goniophotometer device (see two azimuth direction on the diagram without extreme BRDF curves).

[20] These 3D-visualizations of the BRDF values are just for the directional part of reflection, and the diffuse parts of the reflection are not visualized here. This diffuse part is a very small value and similar for all incident directions. The blue underlying flooring in Figure 7–1is an example of this diffuse part.

Since another measured BRDF source of a comparable monitor is not available for comparison in order to ensure that the results are correct and no error has occurred during the process, it is decided to use another accessible measuring option to test the gonio-photometer results. For this reason some measurements are made by means of an integrating sphere. An integrating sphere is a device to measure normal-hemispherical and normal-diffuse transmittance and reflectance (see Appendix F). The hemispherical and diffuse reflectances of the LCD screen for beam incident angle of 8° are measured by integrating sphere. Due to the measuring method of gonio-photometer the directional part of measured reflection is more reliable than the diffuse part. Therefore it was decided to make the comparison between the directional parts of both measurements (gonio-photometer and integrating sphere). The integrating sphere can measure the hemispherical and diffuse reflectance of the screen, therefore by subtracting the value of diffuse reflectance from hemispherical reflectance; the specular reflectance for 8° is calculated:

$$R_{S,8^\circ} = R_H - R_D \qquad (7\text{–}1)$$

$R_{S,8^\circ}$: directional part of reflectance computed for incident angle of 8°
R_H: hemispherical reflectance measured by integrating sphere
R_D: diffuse part of reflectance measured by integrating sphere

Using gonio-photometer measurements the lowest altitude angle of incidence (θ_i), for which the BRDF measurement can be smoothly conducted is 30°. To perform a comparison for 8° between both measuring methods, it is required to estimate the reflectance at 8° by extrapolation from the measured reflectances at 30°, 40°, 50°, 60° and 70°. For this purpose it is necessary first of all to calculate the integral value of the directional parts of the measured BRDF for the mentioned angles (30°, 40°, 50°, 60°, 70°). The integral values of BRDF are computed by an algorithm which is based on a spherical Haar-wavelet method [68]. The estimated 8°-reflectance by gonio-photometer results and the measured 8°-reflectance by integrating sphere show a consistency which underpins the reliability of the gonio-photometer results.

7.1.3 Modeling procedure

For initiating a simulation in RADIANCE simulation program material properties are required. The accuracy of a lighting calculation depends strongly on the accuracy of the surface reflectance model. This reflectance model determines how much light will be returned to the eye from the surface. RADIANCE includes many different surface material types. Each material type has several tunable parameters that govern its behavior [75].

In RADIANCE there is a material type which is called BRTDfunc. BRTDfunc is a broad programmable material that provides all types of reflection and transmission but has some disadvantages [75]. By using BRTDfunc material the directional diffuse reflection (haze reflection) of the material is not taken into account in an ambient calculation. Moreover, to have an accurate simulation of a monitor surface the total reflectance must be computed otherwise the estimated reflection luminance of the simulated screen might be underestimated. Therefore, instead of applying BRTDfunc material for the monitor surface it is made through a mixture of normal material types which would also be considered in the ambient calculation.

In RADIANCE, mixture type is a blend of other materials. For making a "Mixture" in RADIANCE the contribution and influence of each material can be determined either via a simple value or through a complicated function. The materials which are used for generating this mixture for visual display are from two RADIANCE material types called "Plastic" and "Glass". Most of the materials belong to the category of plastic type in RADIANCE. This type is used for materials like plastic, painted surfaces, wood, and non-metallic rocks [75].
Using glass material in the simulation generates one transmitted ray and one reflected ray in a specular direction. The reason for using glass in screen material is to provide a minor specular part in the reflection characteristic of the surface. The process of finding the best possible mixture for the considered screen material is described in the following part.

7.1.3.1 Applying Virtual gonio-photometer (VGPMAP)

Virtual gonio-photometer (VGPMAP) is a computer based tool which has the same functionality as a real gonio-photometer device. VGPMAP is based on RADIANCE and PhotonMapp simulation programs. It is possible to define a light-beam direction and a surface from any kind of material applicable in RADIANCE as input to this program and deliver the reflection distribution function for all azimuth and altitude angles (BRDF) as output. The program enables to change the simulation parameter through a configuration file [60].

In this research study VGPMAP is applied to simplify the procedure of fitting a proper mixture to the measured BRDF data. This mixture is then finalized by optimizing both material and mixture attitudes. For this purpose the reflection (RGB), roughness and specularity of the RADIANCE materials and their mixing order can be parameterized [21] to determine the best material-mixture fitted to

[21] Plastic type in RADIANCE is tunable via its reflectance measure in three RGB channels (Red, Green, and Blue), its fraction of specularity and its roughness value [75].

the measured BRDF. The process of generating an appropriate mixture can be described in the following steps:

- Generating mixture A compatible to the measured BRDF for incident angle of 30° (θ_i = 30°), via evaluation of two following attitudes of the measured material and simulated one:
  - Distribution order of the BRDF values for θ_i = 30° in both measured and simulated cases; this is possible through visualizing the measured and simulated BRDF via the appropriate visualization program
  - Integral value of both measured and simulated BRDF[22]
- Generating of mixture B[23] compatible to the measured BRDF for incident angle 70° (θ_i = 70°), through assessing the above mentioned attitude of both measured and simulated BRDF.
- Deriving a function fit to mix materials A and B to complete the final screen material with the reflection characteristics similar to the measured screen of all incident angles.

From the above mentioned steps, the first and second ones, i.e. generating of the mixture A and B are performed using the VGPMAP tool. This part includes:

- Parameterizing the properties of the chosen RADIANCE materials (one Glass and one Plastic) and their mixing factor;
- Simulating their BRDF values by VGPMAP;
- Comparing the shape and integral of the simulated BRDF to the measured BRDF for each incident angle (30° and 70°);
- Repeating the whole above process to achieve the best match accepted as material A and B

Figure 7–4 illustrates the visualizations of the two achieved mixture fitted to the measured BRDF for θ_i =30° and θ_i =70°. The procedure of the third step is described in the next part. The whole process of generating the material model is summarized in the flowchart demonstrated in Figure 7–3.

[22] The Integral measure used for this assessment is computed from the directional part of the reflection and not from the whole reflection amount. The directional part is the most effective part of the reflection (see figure 6-6).

[23] The mixture-materials A and B are not functional mixture types in Radiance. They are made by a less complicated mixture type which requires just the contribution amount of either material to the mixture definition.

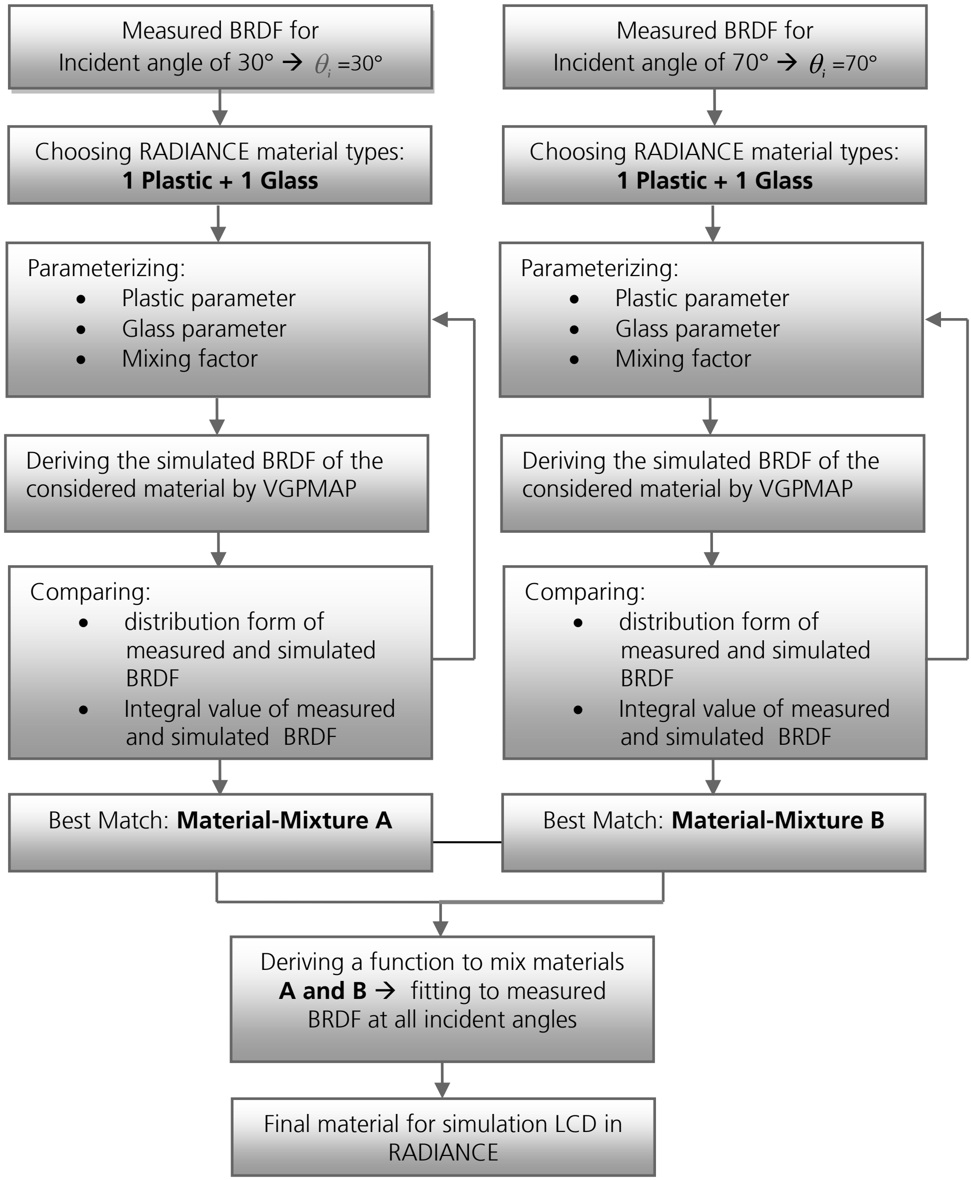


Figure 7–3: Flowchart showing the procedure of generating the material model from the measured BRDF.

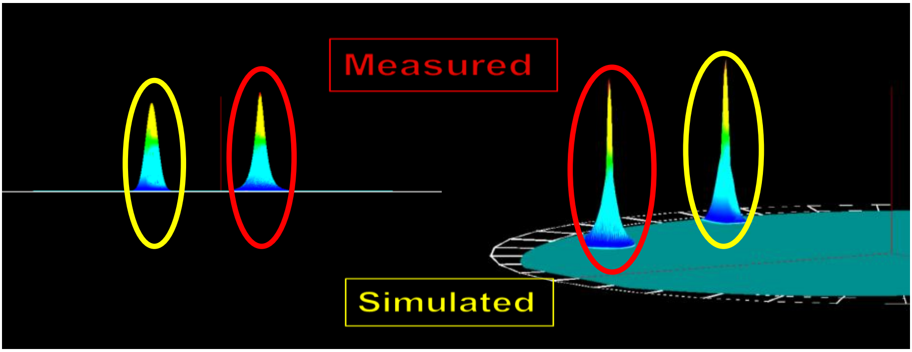


Figure 7–4: Left: 3D-Visualization of BRDF values (only the directional part of the reflection) of the measured screen material and simulated material-mixture A at incident angle θ_i=30°. Right: 3D-Visualization of BRDF values (only the directional part of the reflection) of measured screen material and simulated material-mixture B at incident angle θ_i =70°.

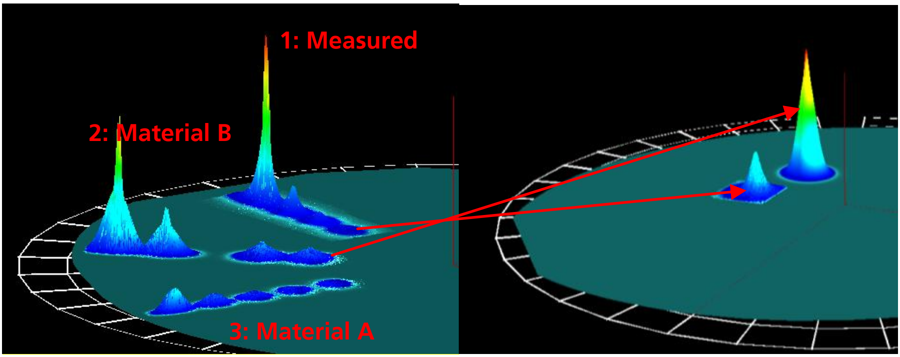


Figure 7–5: Left: 1: measured BRDF for all incident angles (θ_i =30°, 40°, 50°, 60°, and 70°)
2: simulated BRDF of the material B for the same incident angles.
3: simulated BRDF values of material A
Right: a close up view from the measured BRDF at incident angle 30° and simulated BRDF of mixture B at θ_i =30°. As visible, the mixture B which has been developed compatible to the reflection behavior of the screen at θ_i =70°, would not match the measured BRDF for incident angle 30°.

7.1.3.2 Fitting function

Figure 7–6 shows three diagrams displaying the peak values of BRDF in all three cases, i.e. measured monitor material and simulated material-mixtures A and B. The peak values are another measure to characterize the BRDF apart from the integral values. In fact the peak values have proven to be a better representative to show how the shape changes at different incident angles, compared to integral values and therefore are used to complete the final mixing process.

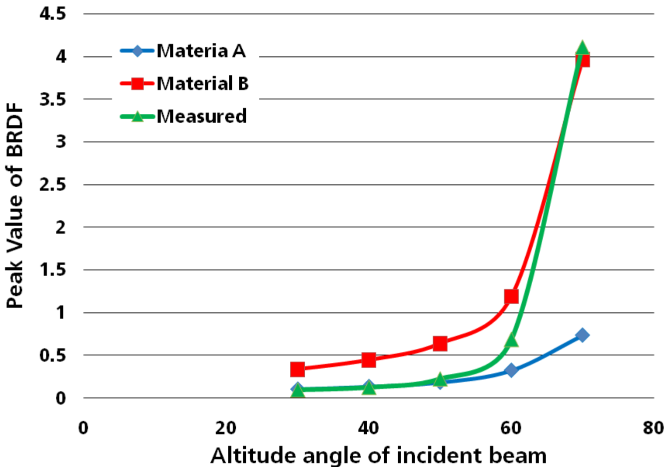


Figure 7–6: Diagram shows the BRDF peak values of the measured screen-material and both simulated materials A and B.

The last step of the material model development is developing a fitting function for mixing both materials A and B which represent the reflection behavior of the measured screen-material at all incident angles. The available data for performing this development is:

- The peaks of the modeled BRDF for incident angles of 30° and 70°
- The peaks of the measured BRDF for all incident angles of 30°, 40°, 50°, 60° and 70°

Therefore the next steps are:

- Considering a peak factor between 0 and 1 for all incident angles by which:
    - PF=0 represents the peak of the modeled BRDF for the lowest incident angle.
    - PF=1 represents the peak of the modeled BRFD for the highest incident angle.
- Estimation of the PF for all other incident angles using the following equation:

$$PF_i = \frac{(P_{M,i} - P_A)}{(P_B - P_A)} \qquad (7\text{–}2)$$

PF_i: estimated peak factor of modeled BRDF for the incident angle of θ_i
$P_{M,i}$: peak of measured BRDF for the incident angle of θ_i
P_A: peak of simulated BRDF of Material A for incident angle of 30°
P_B: peak of simulated BRDF of Material B for incident angle of 70°

- Deriving a function of incident angle which fits to the obtained peak factors of all modeled BRDF; the diagram illustrated in Figure 7–7, shows this fitting function:

$$f = \frac{e^{a+bX}}{1+e^{a+bX}} \tag{7–3}$$

a, b: fitted parameters
X: independent variable (in this case altitude incident angle)

The best achieved values for "a" and "b" in this case are:

- a= -16.35
- b= 0.27

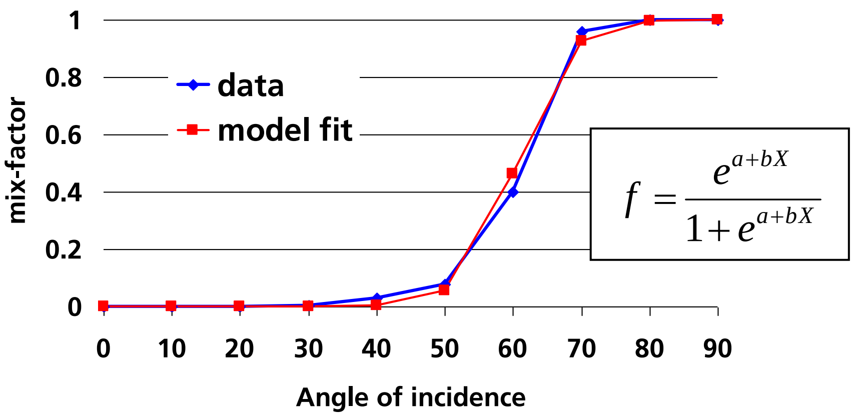


Figure 7–7: Diagram shows the developed function file for mixing two materials [51].

This mixing function can be given to RADIANCE program via a specific function file format with ".cal" suffix. These function files in RADIANCE are usually used to specify mathematical formulas and relations for procedural textures, patterns and surfaces [74].

7.2 Simulation-based veiling glare evaluation

In this part of study the phenomenon of veiling glare on monitor screens is to be evaluated via lighting simulation. These evaluations are to test the developed material model of LCD and to compare this model with two other available models in respect to their reflection behavior and their abilities to deliver reliable results by contrast evaluation.

The first step in simulation-based veiling glare evaluation is defining the location, geometry and materials of the room and visual display and specifying the desired lighting situation. The geometrical and photometrical properties of the office room used for these simulations are identical to the test room described in previous chapters (2, 3 and 4).

Figure 7–8: A visual disply is located in an examplar office room with a fully glazed façade facing south. The view direction is parallel to the façade. The geographical location of the room is Freiburg; Simulation is conducted under two different daylight conditions with a sunny sky:
Solar altitude(θ_s = 20°) and solar azimuth (φ_s =60°)
Solar altitude (θ_s = 30°) and solar azimuth (φ_s =-10°)

7.2.1 Determining a pattern as screen image

At the start is the contrast evaluation on the visual display via a simulation. First a pattern shall be considered as a screen image which affords both low and high state luminances. Two different methods are to be used for generating such a pattern:

- Conducting the simulation with the visual display without any screen image and evaluating the computed values obtained achieved from the simulation assuming an imaginary pattern. The application of this option will be explained in detail in chapter-8.

- Generating an image with the RADIANCE program and then fix it on the screen and implement all the following simulations with the visual display included this image. This method is applied for the simulations in this part of the research work.

The image considered as the screen image is illustrated in Figure 7–9. The screen image generated and used for this purpose encloses dark and bight stripes; each stripe has a width of few pixels. This image has been generated by means of a RADIANCE pattern type named "Brighttext" to get a pure, pixilated, monochrome image.

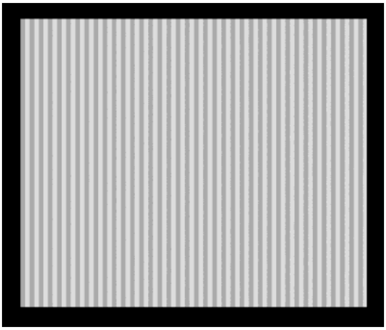


Figure 7–9: The image considered as a display image. The width of the bright and dark stripes is equal to a few pixels. The initial contrast ratio between the two adjacent strips was set up close to the standard minimum required contrast.

Using this pattern (or any similar pattern) would afford an initial low and high state luminance, and hence an initial contrast ratio equal to:

$$CR_1 = \frac{L_{H,1}}{L_{L,1}} \tag{7–4}$$

CR_1: initial contrast ratio
$L_{H,1}$: initial luminance of bright part [cd/m^2]
$L_{L,1}$: initial luminance of dark part [cd/m^2]

7.2.2 Calculation of the contrast after reflection and contrast deficiency

For computing the contrast ratio between the area with low- and high state luminance on the computer screen after reflection the following procedures are necessary:

- To determine the initial luminance of a low- and high state. For this purpose firstly one simulation process shall be performed in a completely darkened room to compute the luminance of both bright- and dark areas from a specified view point without considering the reflection.

- To perform the simulation process again under the desired lighting condition. This simulation would deliver the value of the reflection and the final contrast ratio.

The next step after computing the reflection is the evaluation and estimation of the contrast deficiency. For this purpose the computed contrast between the bright- and dark areas across the screen after reflection will be compared with the minimum required contrast in order to determine the area in which the actual contrast is less than the recommended contrast requirement. These parts of the screen are called "area with contrast deficiency" or "area with veiling glare". This procedure is described in more detail in the next part with three material models and two contrast models.

7.2.3 Comparison of three different material models for a LCD

This part is giving a description of a comparative contrast evaluation which is implemented for the following options:

- ✓ Three simulation model of a visual display derived thorough three different measurement methods. The type of the LCD is an "EIZO FlexScan L56 LCD".
- ✓ Two different standard models of minimum required contrast stated in the "ISO 13406-2" and "ISO 9241-303 (Annex D)" [27, 36].

- **VDT-Model 1**

The Material model 1 used for visual display is a mixture of plastic and glow. Measured data of this model are direct reflectance value and total reflectance value measured by integrating sphere. As an alternative measurement method, Spectral-Reflectometer can also be used.[24]

- **VDT-Model 2**

The monitor model 2 is a mixture of plastic, glass and glow. Measured data of this model are illuminance at screen plane and luminance of the screen. There are two layers. In the background there is a glow with a picture and In the front of glow there is a mixture of glass and plastic material. The reduced refraction index of the glazing takes into account the anti reflective coating of the surface. The mixture value was set after luminance measurements under different lighting conditions [84]

- **VDT-Model 3**

Material model 3 is the model which was developed specifically for this study by means of gonio-photometer and was thoroughly described in the part "7.1-Measurements and modeling of a LCD monitor"

[24] This model has been originally developed by Gregory Ward Larson, by means of a Spectral-Reflectometer for another monitor type. In this study his method was applied and modified for EIZO FlexScan L56 LCD using the results of integrating sphere to make it comparable with other models of the same LCD type.

- **Contrast Model 1**

Contrast Model 1 is the "minimum required contrast" according to the ISO-standard 13406-2 [27] (equation 2–7)

- **Contrast Model 2**

This model of minimum contrast is according to the standard "ISO 9241-303 (Annex D)" [36] (equation 2–11):

7.3 Results

The evaluations of this comparative study are based on the procedure described in part 7.2.2 and the pattern used as screen image is the image illustrated in Figure 7–9. The secondary contrast ratios after reflection are calculated using the simulation results and are compared with the minimum contrast to determine the amount of contrast deficiency using the following calculation:

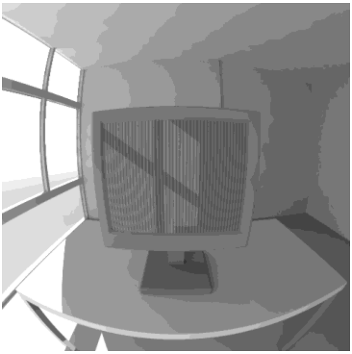
$$CR_2 < CR_{\min} \Rightarrow CD = CR_{\min} - CR_2 \qquad (7\text{–}5)$$

$$CR_2 = \frac{L_H + L_r}{L_L + L_r}$$

CR_2: contrast ratio after reflection while the CR_1 is the contrast without reflection (equation 7–4)
CR_{min}: minimum required contrast according to ISO- standard models
CD: contrast deficiency
L_r: reflected luminance [cd/m^2]

The area of the computer screen with contrast deficiency can also be considered as the area with veiling glare problem. The images illustrated in Figure 7–10 to Figure 7–21 are the simulated pictures of the same visual display modeled with three mentioned material models; they are simulated under two different daylight conditions with the respective contrast deficiency diagrams based on two different standard contrast models. The resolution of the simulated computer screens is 1024 X 768. The colorful areas on the diagrams represent the screen-area with contrast deficiency and the magnitude of contrast deficiency is scaled according to the color-scale demonstrated on the upper-right side of the diagrams.

The new developed MRC model explained in chapter-7 is not used for these evaluations. This study was completed before the final development of the MRC model and the decision was made that it be kept to its original layout. In fact the contrast model does not have an important role within this evaluation and is used just as a basis for the comparisons (the main purpose is evaluating the influence of the material model). Therefore the results which are based on both old and new standard contrast models are illustrated to provide an opportunity for a comparison of the standard models (between the new and the former one) and simultaneously for a comparison of the different material models. But the main simulation studies of this research work (that will be explained in the next chapter) are implemented using the newly developed MRC model. As demonstrated in the following images the material model (or in other words the method to develop the material model of a visual display) could have a significant influence on the estimation of contrast deficiency and veiling glare.



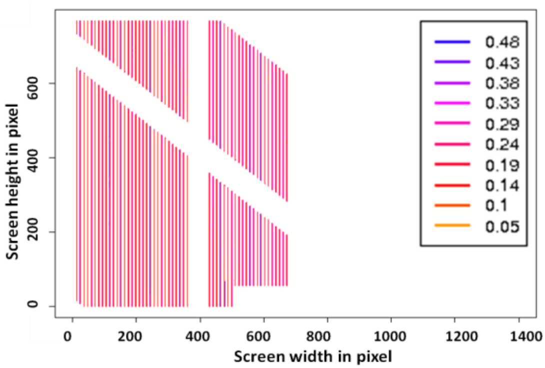
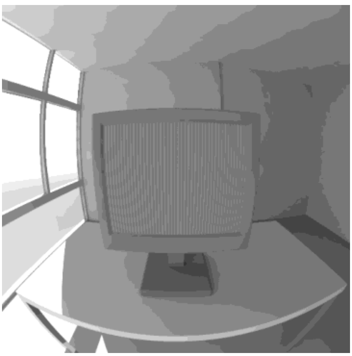


Figure 7–10: Left: VDT model 1, under daylight conditions: θ_s= 20°; φ_s= 60°. Right: contrast deficiency diagram based on contrast model 1.



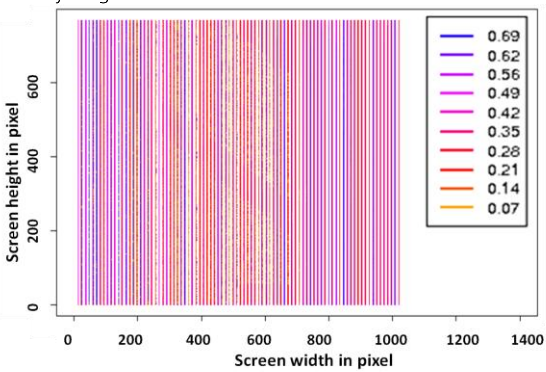


Figure 7–11: Left: VDT model 2 under daylight conditions: θ_s= 20°; φ_s= 60°. Right: contrast deficiency diagram based on contrast model 1.

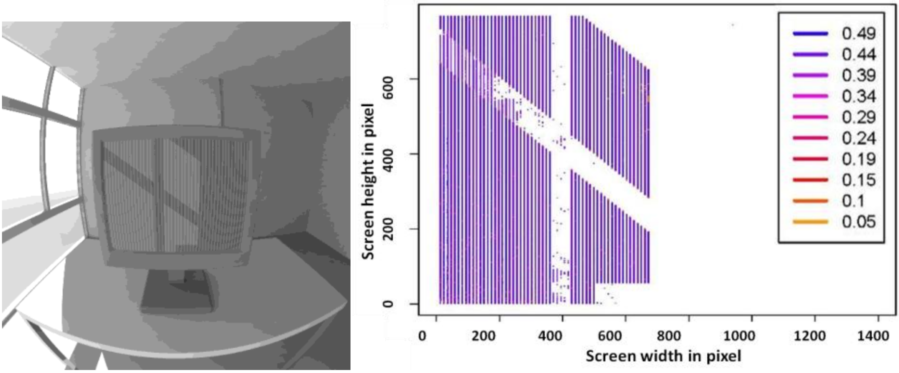


Figure 7–12: Left: VDT model 3 under daylight conditions: θ_s= 20°; φ_s= 60°. Right: contrast deficiency diagram based on contrast model 1.

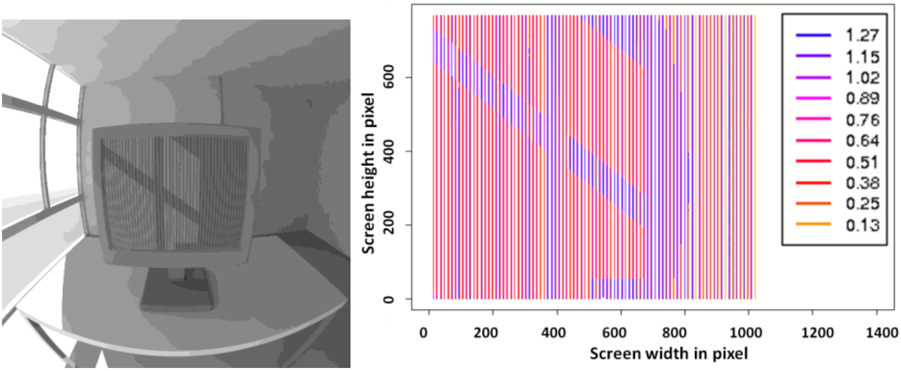


Figure 7–13: Left: VDT model 1 under daylight conditions: θ_s= 20°; φ_s= 60°. Right: contrast deficiency diagram based on contrast model 2.

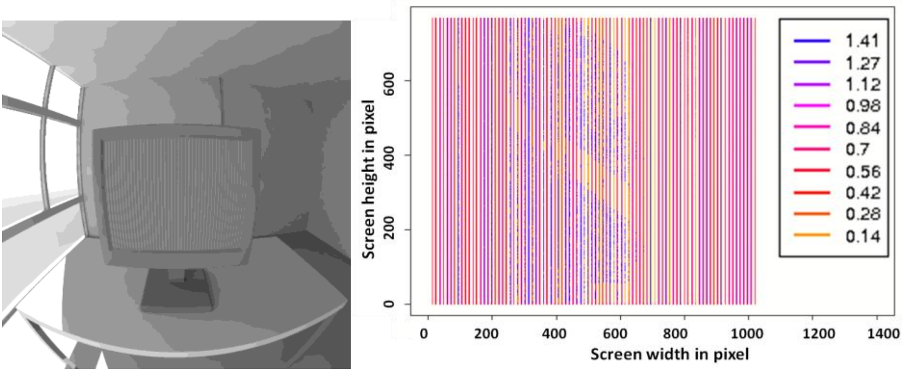


Figure 7–14: Left: VDT model2 under daylight conditions: θ_s= 20°; φ_s= 60°. Right: contrast deficiency diagram based on contrast model 2.

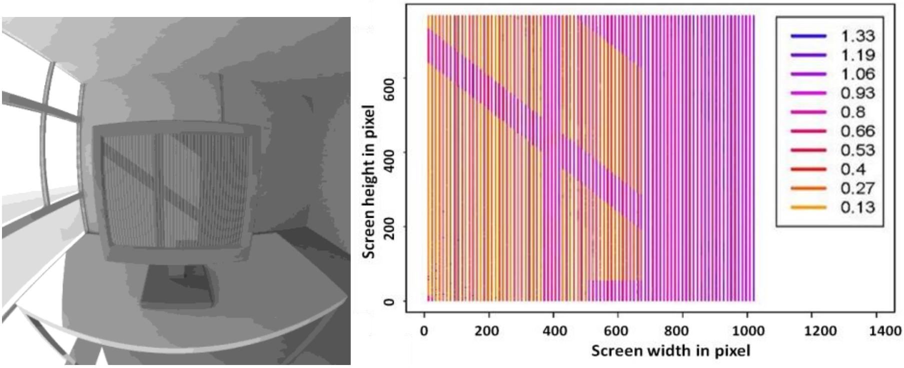


Figure 7–15: Left: VDT model 3; under daylight conditions: θ_s= 20°; φ_s= 60°.
Right: contrast deficiency diagram based on contrast model 2.

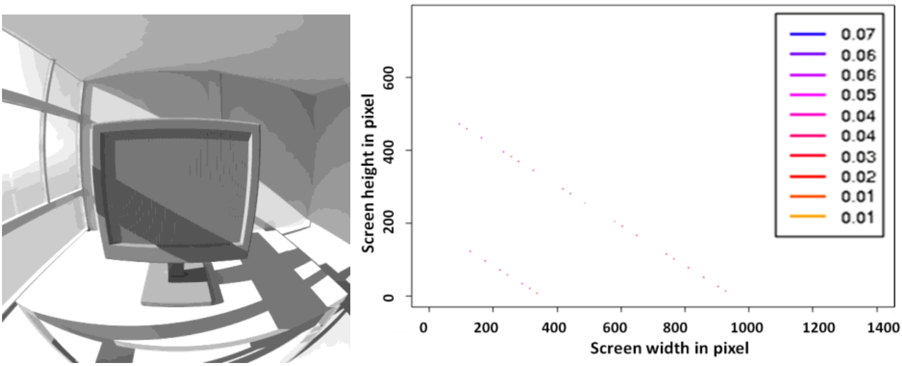


Figure 7–16: Left: VDT model 1 under daylight conditions: θ_s = 30°; φ_s =-10°.
Right: contrast deficiency diagram based on contrast model 1.

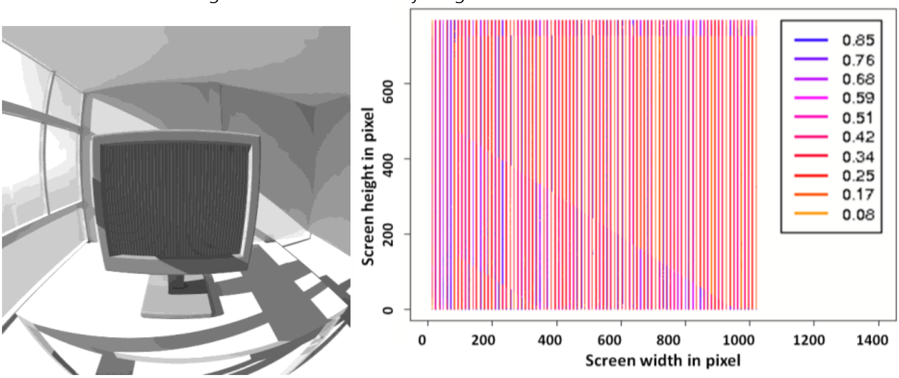


Figure 7–17: Left: VDT model 2, under daylight conditions: θ_s = 30°; φ_s =-10°.
Right: contrast deficiency diagram based on contrast model 1.

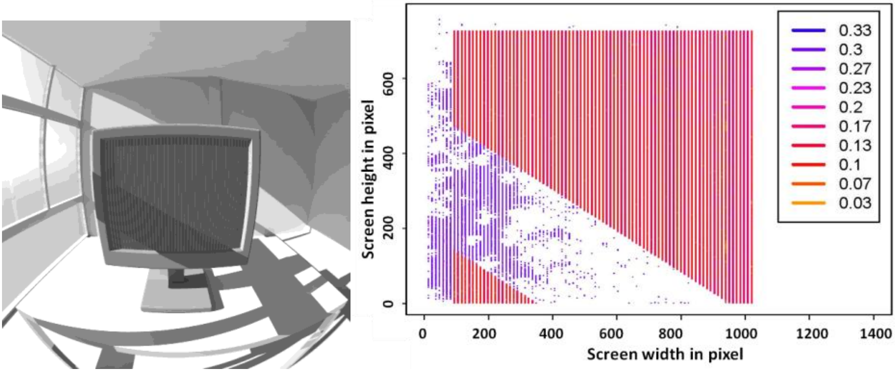


Figure 7–18: Left: VDT model 3, under daylight conditions: $\theta_s = 30°$; $\varphi_s = -10°$.
Right: contrast deficiency diagram based on contrast model 1.

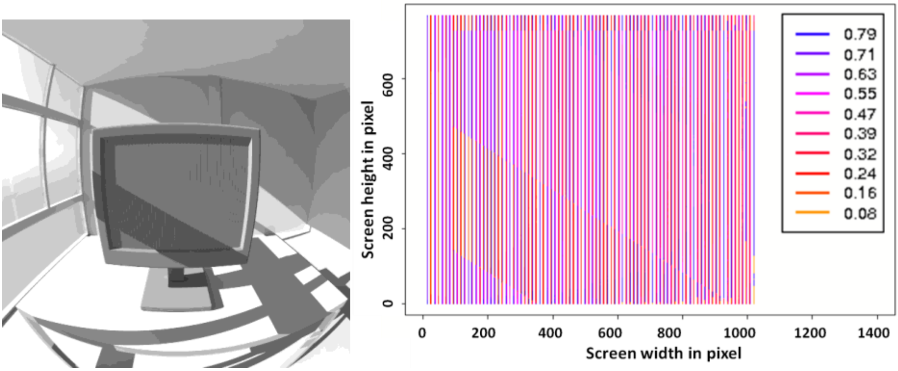


Figure 7–19: Left: VDT model 1; under daylight conditions: $\theta_s = 30°$; $\varphi_s = -10°$.
Right: contrast deficiency diagram based on contrast model 2.

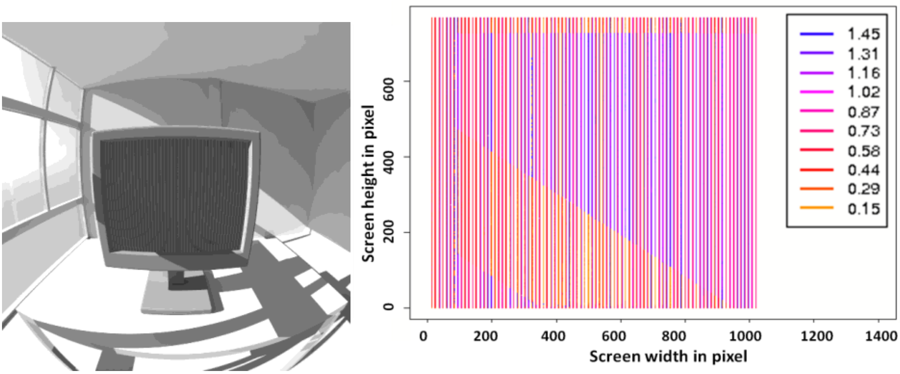
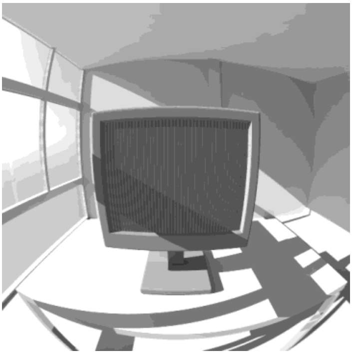


Figure 7–20: Left: VDT model 2; under daylight conditions: $\theta_s = 30°$; $\varphi_s = -10°$.
Right: contrast deficiency diagram based on contrast model 2.



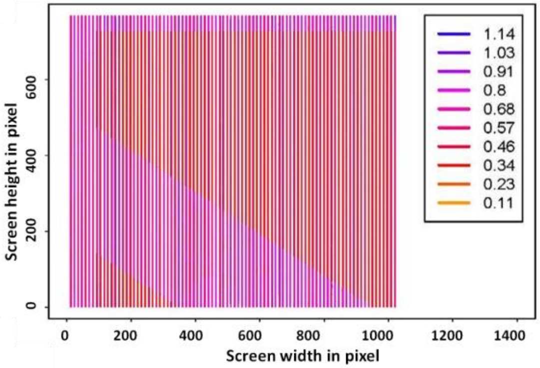


Figure 7–21: Left: VDT model 3 under daylight conditions: θ_s = 30°; φ_s =-10°.
Right: contrast deficiency diagram based on contrast model 2.

7.4 Summary and discussion

In the first part of this chapter a modeling procedure was explained to generate a material model for a computer screen with an accurate optical property. In order to show the importance of a precise model in the second part a simulation study is conducted to compare the newly modeled screen with two other models of the same screen type. The simulation results show a significant difference in the outcomes.

Apart from various VDT models two different contrast models are also evaluated in this study (based on standard models). This evaluation makes the possibility of presenting an example of how significant the contrast model could affect the veiling glare prediction. To facilitate the comparison simulation results are evaluated and summarized in the following tables. These tables include the average value of contrast deficiency and the problematic fraction of the screen (the fraction with contrast deficiency problem) for all of the simulated cases.

As displayed in the following tables the evaluation results of visual quality on a computer screen is greatly dependent on how accurately the screen is modeled. For example, as seen in Table 7-3 the use of material model 1 results in an average contrast deficiency of 0.068 and the problematic fraction of 0.03%, while the output of the same evaluation with material models 2 and 3 (other models from the same display) are 99.9% and 92% respectively - this is a significant difference. Furthermore, the difference between two standard contrast models in estimating the minimum required contrast values, illustrated in Figure 2–4 is evident in the results of this study. By using the contrast model 1 (ISO 13406-2) as the basis for evaluations - with both lighting conditions and all three display models the predicted problem is smaller compared to the contrast model 2 (ISO 9241-303).

Table 7-1: Average contrast deficiency and problematic screen fraction of all three material models simulated under daylight condition (θ_s =20°, φ_s =60°); evaluations are based on contrast model 1.

Contrast Model 1 Sun position: θ_S = 20° φ_S =60°			
	VDT model 1	**VDT model 2**	**VDT model 3**
Average value of contrast deficiency	0.0713	0.313	0.086
Screen fraction with veiling glare	49.7%	99.9%	61%

Table 7-2: Average contrast deficiency and problematic screen fraction of all three material models simulated under daylight condition (θ_s =20°, φ_s =60°); evaluations are based on contrast model 2.

Contrast Model 2 Sun position: θ_S = 20° φ_S = 60°			
	VDT model 1	VDT model 2	VDT model 3
Average value of contrast deficiency	0.696	1.157	0.815
Screen fraction with veiling glare	100%	100%	100%

Table 7-3: Average contrast deficiency and problematic screen fraction of all three material models simulated under daylight conditions (θ_s =30, φ_s = -10°); evaluations are based on contrast model 1.

Contrast Model 1 Sun position: θ_S =30° φ_S = -10°			
	VDT model 1	**VDT model 2**	**VDT model 3**
Average value of contrast deficiency	0.068	0.287	0.051
Screen fraction with veiling glare	0.038%	99.9%	92%

Table 7-4: Average contrast deficiency and problematic screen fraction of all three material models simulated under daylight conditions (θ_s=30°, φ_s= -10°); evaluations are based on contrast model 2.

Contrast Model 2 Sun position: θ_S = 30° φ_S =-10°			
	VDT model 1	VDT model 2	VDT model 3
Average value of contrast deficiency	0.628	1.179	0.808
Screen fraction with veiling glare	100%	99.9%	100%

Taking the results into consideration the conclusions of this chapter can be summarized in the following points:

- The process of modeling the material of visual display might lead to entirely different outcomes. The differences can be in the average value, in distribution order and in problematic screen fraction. This shows the importance of using an accurate material model for performing veiling glare study. Otherwise the study could lead to the incorrect problem-estimation and further wrong decisions based on an incorrect estimation.

- The contrast model also plays a significant role in the estimation of the screen quality in the veiling glare study. Therefore, such as with the material model an inaccurate contrast model could also lead to the wrong problem-prediction and further incorrect decisions.

8 Application of the developed model

This chapter is the last step in realizing the defined purpose in the research strategy which was development of a method to evaluate visual quality of computer screens in the office spaces. The main intention of this chapter is to provide an outlook with respect to the application and functionality of the newly developed model for designing the spaces that involve onscreen visual tasks. In fact the developed MRC model could be applied as an aiding tool to facilitate the ergonomic design of the spaces containing on-screen visual tasks by providing more acceptable daylight inside the room and improving visual comfort.

A very typical space with an on-screen visual task is office space; this model can be applied for improving the design strategy of the office spaces concerning the following criteria:

- Layout of the space:
    - Location and orientation of the desks in the room
    - Location and orientation of the visual display on the desk
- Size and dimension of the window façades
- Type and application of the shading systems

To show the applicability of the developed model on design-improvement of the office spaces an example is presented in this chapter. This example is different from the simulation study performed in chapter-7. The purpose of the simulation study in chapter-7 was an assessment of the effect of a monitor model and the contrast model on veiling glare prediction; it was conducted in one geometrical scenario and under two separate lighting conditions. However, this chapter deals with the concept of “veiling glare evaluation method “and its applicability with regards to design/layout of the spaces.

8.1 Method

A standard office room was selected for implementing this part of the study. An annual simulation-based study is performed for the standard office by means of DAYSIM; which is a RADIANCE based tool to enable annual lighting simulations. The output of DAYSIM is a matrix of the desired lighting factors (Illuminance or Luminance) in defined time series e.g. hourly time steps. DAYSIM uses the daylight coefficient method described in [64, 63]. The results of the annual simulations of the visual display are used for making an evaluation on veiling glare problem throughout the year based on the developed MRC model.

8.1.1 Model set up

The office room which is modeled to be used in the simulation study is a standard single-office with a south-facing window façade. The geometrical and photometrical features of the office are the following:

- Geometrical features:
    - Office depth: 4.20 m
    - Office width: 3.65 m
    - Office height: 2.85 m
- Photometrical features:
    - Wall: purely diffuse without specularity with ρ_{wall}=0.55
    - Floor: purely diffuse without specularity with ρ_{floor}=0.34
    - Ceiling: purely diffuse without specularity with $\rho_{ceiling}$=0.80

Figure 8–1shows the plan of the office. This size of the window is considered as a variable in this study. The location and photometrical property of the desk in the office are the following:

- Distance of the workplace to the window: 1.3m
- Height of the workplace: 0.8m
- Height of the eye position: 1.35m
- ρ_{desk}= 0.50 including 0.02 specular reflection

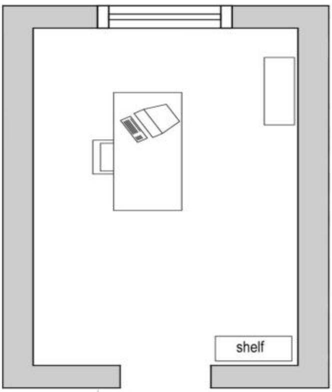


Figure 8–1: Plan of the modeled standard office room for the simulations. The window façade represents the punched window façade which is one of the two variants of a considered window size in this study.

8.1.1.1 Variables

In order to provide a comparison study three elements are considered as a variable in this study - the size of the window façade, utilization of shading system and the orientation of visual display related to window façade. These variables altogether generate 24 variants summarized in Table 8-1. More details about the variables are described in the subsequent parts.

Window façade Size

Two different window types are used for this simulation study. One of them is a fully glazed façade and the other one is a punched window façade with the dimensions 1.642m x 1.336m. Both cases are solar control double glazing with the visual transmittance of 54%. The glazing areas of the windows are as following:

- Large glazing area, fully glazed façade: 9.62 m²
- Small glazing area, punched window façade: 2.19 m²

Shading system

The simulation study is performed once without any shading system, and once with the venetian blinds with a fixed angle of 45 degrees (in cut-off condition) installed outside the room. The modeled venetian blinds used for this study are the standard white venetian blinds with the following characteristics:

- Type: Venetian blinds, 80 mm, convex
- Color: White (RAL 9016, visual reflectance ρ_{Vis}=84 %)
- Transmittance: Tilt dependent (in this study the venetian blinds are simulated in cut-off positions)

Visual display location

The visual display used for this simulation study is the same type measured within the framework of this research and was explained in chapter-6. Eight different orientations are considered for the visual display on the work place. The schematic images of these orientations are demonstrated in Figure 8–2 to Figure 8–5.

Figure 8–2: Left: orientation 1; view direction parallel to window, toward west.
Right: orientation 2; view direction 45° toward the south-west.

Figure 8–3: Left: orientation 3; view direction vertical to window toward south.
Right: orientation 4; view direction 45° toward south-east.

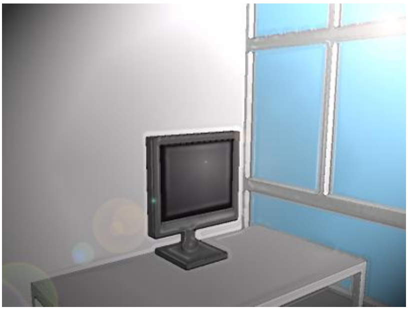


Figure 8–4: Left: orientation 5; view direction parallel to window, toward east.
Right: orientation 6; view direction 45° toward north-east.

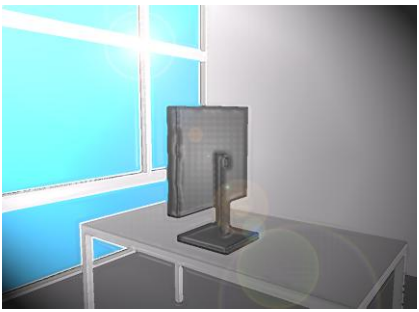


Figure 8–5: Left: orientation 7; view direction toward north.
Right: orientation 8; view direction 45° toward north-west.

View position relative to the computer screen in all variants is as the following:

- View distance from the middle of monitor: 50 cm
- View declination angle up to the normal of the screen : 12.5°

In Table 8-1 all 24 variants that are simulated and evaluated are listed.

Table 8-1: List of simulated and evaluated variants use for veiling glare study.

	Window size	Shading system	VDT orientation
Variant 1-1	Large	-	1
Variant 1-2	Large	-	2
Variant 1-3	Large	-	3
Variant 1-4	Large	-	4
Variant 1-5	Large	-	5
Variant 1-6	Large	-	6
Variant 1-7	Large	-	7
Variant 1-8	Large	-	8
Variant 2-1	Large	Venetian blinds	1
Variant 2-2	Large	Venetian blinds	2
Variant 2-3	Large	Venetian blinds	3
Variant 2-4	Large	Venetian blinds	4
Variant 2-5	Large	Venetian blinds	5
Variant 2-6	Large	Venetian blinds	6
Variant 2-7	Large	Venetian blinds	7
Variant 2-8	Large	Venetian blinds	8
Variant 3-1	Small	-	1
Variant 3-2	Small	-	2
Variant 3-3	Small	-	3
Variant 3-4	Small	-	4
Variant 3-5	Small	-	5
Variant 3-6	Small	-	6
Variant 3-7	Small	-	7
Variant 3-8	Small	-	8

8.1.1.2 weather date and sky model

A weather dataset of Freiburg based on hourly values is used for these simulations. The dataset is generated by means of the program called Meteonorm [48]. This weather dataset is based on hourly direct horizontal radiation and diffuse horizontal radiation (these data are required to perform the annual simulation by the DAYSIM simulation program).

8.1.1.3 Rendering parameters

For performing this simulation study the following rendering parameters for

RADIANCE are used. According to the author's former experiences with this simulation program these settings seems to deliver reliable results for the considered office by given room and shading geometries but are not expected to be the default settings for all office scenarios. The settings are:

- Ambient bounces (-ab): 5
- Ambient divisions (-ad): 4096
- Ambient super-samples (-as): 256
- Ambient resolution (-ar): 256
- Ambient accuracy (-aa): 0.1
- Limit reflections (-lr): 6
- Specular threshold (-st): 0.15
- Specular jitter (-sj): 1.0
- Direct jitter (-dj): 0.00
- Direct sampling (-ds): 0.2
- Direct pretest density (-dp): 512

8.1.2 Step by step procedure

After modeling the respective geometry files for all variants the subsequent procedure is implemented for all 24 different variants to derive the annual veiling glare profile of each variant:

- Determine the equal size unit areas all over the screen for positioning the sensors. To compute the luminance of the screen by DAYSIM it is necessary to define the sensor positions on the screen. The sensor positions in this study are considered in the central points of the defined unit areas. Since an ordinary visual target on VDT by conducting a reading task is a character, it was decided to consider the view angle of the unit area equal or less than the view angle of a character. According to standards (ISO 13406-2) [27] the character height is suggested to be 16 minutes of arc. For this evaluation the width and height of the unit areas is considered equal to 10 min of arc. According to the screen size and view distance the dimension of the unit area is computed (see Figure 8–6).

$$D_{VF} = Dist \bullet 2 \cdot \tan(\frac{\alpha}{2}) \qquad (8–1)$$

α: view angle (10 min of arc)
D_{vf}: dimension of view field (considered unit area in Figure 8–6)
Dist.: distance between viewpoint and screen

- Make the file of all ray directions start at eye position and end at the central point of each unit area; use this file as sensor file in DAYSIM simulations to calculate the reflected-luminance on each unit area of the screen at each time step during the year.

- Determine the vertical illuminance at eye position for any time step and then convert it to an average environmental luminance by:

$$L_E = \frac{E_V}{\pi} \tag{8–2}$$

L_E: average environment Luminance [cd/m^2]
E_v: vertical illuminance at eye position [lux]

- Modify the reflection files by DAYSIM simulations according to an imaginary chess shape format illustrated in Figure 8–6. That means assuming two initial values for LL and LH and adding them to the reflection luminances in alternative order. The values of initial LL and LH in this study are L_L=10cd/m^2 and L_H=80cd/m^2 in positive polarity. The reason for this selection is to have an initial contrast ratio which is an ordinary range and realistic for on-screen tasks.

- To confirm these assumptions MRC and primary contrast (before reflection) are calculated for several L_L and L_H assuming different L_E. This is to select the values by which the primary contrast is not less than MRC. The values of 10cd/m^2 and 80cd/m^2 showed also to be good selections in this respect.

- Calculate the contrast ratio and the minimum required contrast based on the new developed MRC model, for any two adjacent areas.

- Determine the area of the screen on which the contrast is less than MRC at any time step; these areas are problematic as they are affected by veiling glare phenomenon, and the magnitude of veiling glare in this study is defined as the relative contrast deficiency and formulated as the following:

$$if \quad CR < MRC \Rightarrow RCD = \frac{(MRC - CR)}{MRC} \tag{8–3}$$

RCD: relative contrast deficiency to express the veiling glare magnitude (if CR > MRC, then RCD=0)

- Compute the average RCD value of the whole screen at any time step to facilitate a comparison between all variants in respect of occurring veiling glare during the year.

- Determine the following values for any variant:
    - Average annual veiling glare (RCD)

- Fraction of the year in which the screen is confronted with veiling glare problem
- Highest value of RCD (averaged for the whole screen) in all time steps

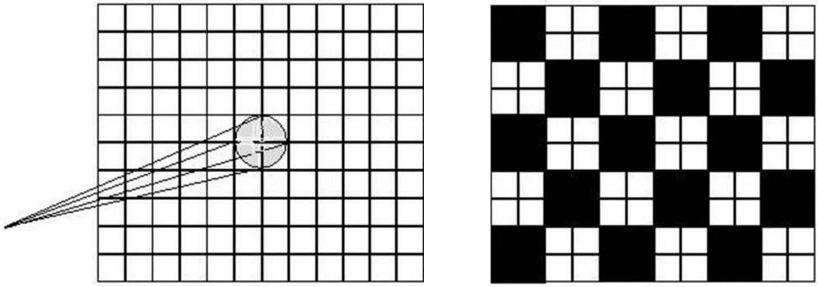


Figure 8–6: Left: considering a view field of about 10 minute of arc.
Right: assumed chess shape file of dark and bright areas of equal size to considered view field.

The explained procedure is summarized in the chart illustrated in Figure 8–7. This procedure is a manually performed process which is made by using different programs and tools e.g. RADIANCE, DAYSIM, OCTAVE, C and AWK. These different steps could cause some difficulties in performing the analysis and make it dependent on the user's knowledge of the respective programs. In order to simplify the evaluation process and convert it to a more general-used method a tool is developed which is explained in the part *"8.4-Automated procedure"*.

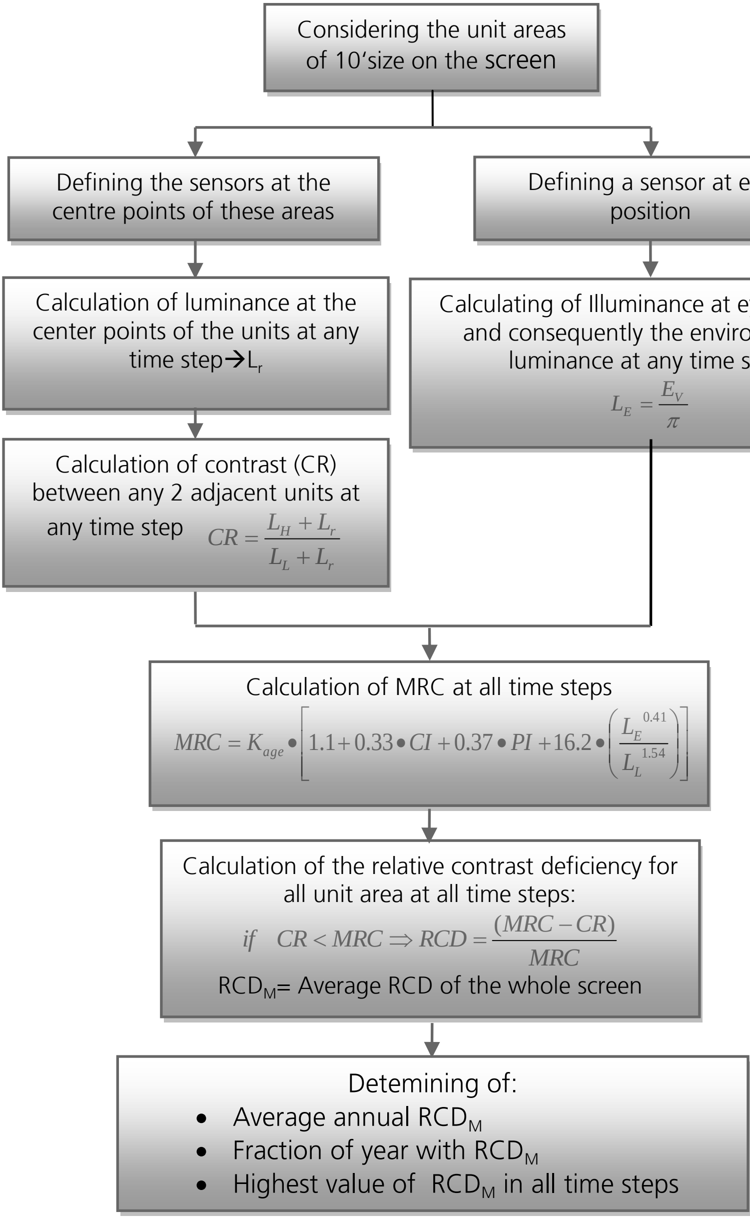


Figure 8–7: The chart shows the procedure of the calculation of the annual veiling glare profile for all variants.

8.2 Results

The outcomes of the performed study according to the mentioned procedure are the text files including all the calculated RCD values for all unit areas at each time step throughout the year. In order to facilitate the comparison between all variants the values of RCD across the visual display are averaged for each time step and the calculated mean RCD value (RCD_M) is considered as the representative veiling glare value at each time step.

The illustrated diagrams in Figure 8–8 to Figure 8–31 demonstrate the distribution of the mean RCD throughout the year for all 24 variants. The y-axes in the diagrams represent the hours-of-day from 8am to 7pm and X-axes stand for the days for all 12 months. The color schemes for these graphs are chosen so that the black-color corresponds to "no-problem" and the yellow-color represents the "maximum occurred problem". The data in these graphs are the mean-value of RCD (RCD_M) which has been averaged throughout the screen area. The scales of the diagrams are set to the maximum occurred RCD_M for each case. RCD_M could be theoretically between 0 and lower than 1 (according to equation 8–3). RCD value equal to zero means that CR is greater than MRC (actual contrast in higher than required contrast) and there is no problem.

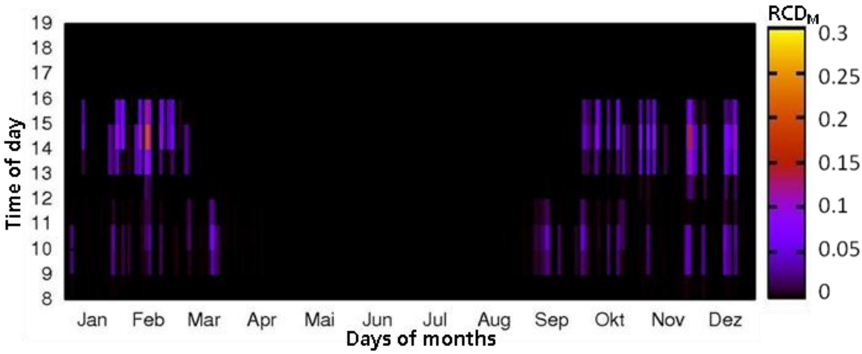


Figure 8–8: Annual veiling glare (RCD_M) profile of variant 1-1: fully window façade without venetian blinds; screen position 1 (rated 16th from 24).

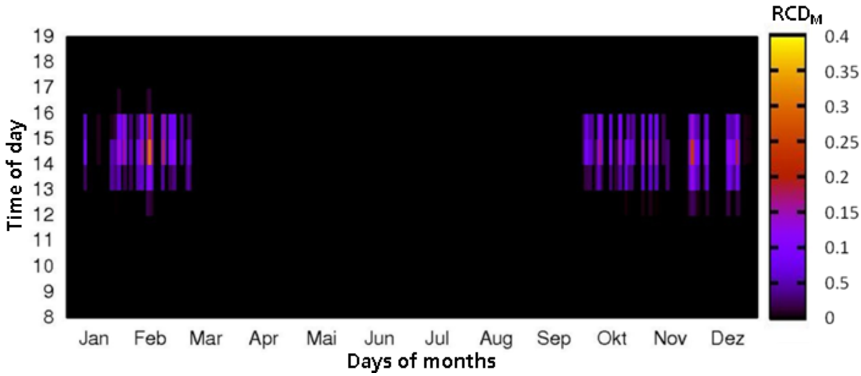


Figure 8–9: Annual veiling glare (RCD$_M$) profile of variant 1-2: fully window façade without venetian blinds; screen position 2 (rated 13th from 24)

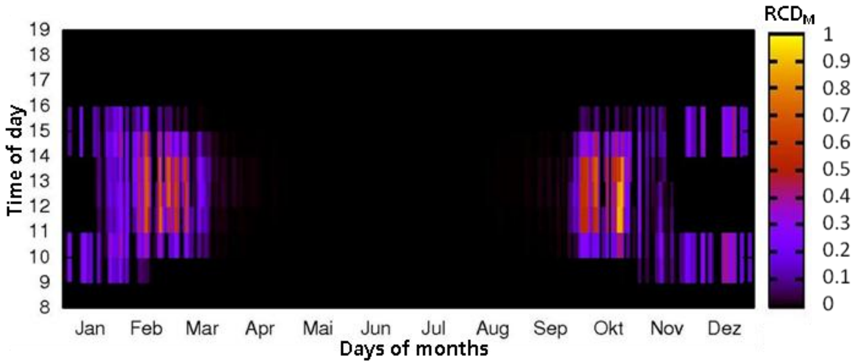


Figure 8–10: Annual veiling glare (RCD$_M$) profile of variant 1-3: fully window façade without venetian blinds; screen position 3 (rated 24th from 24)

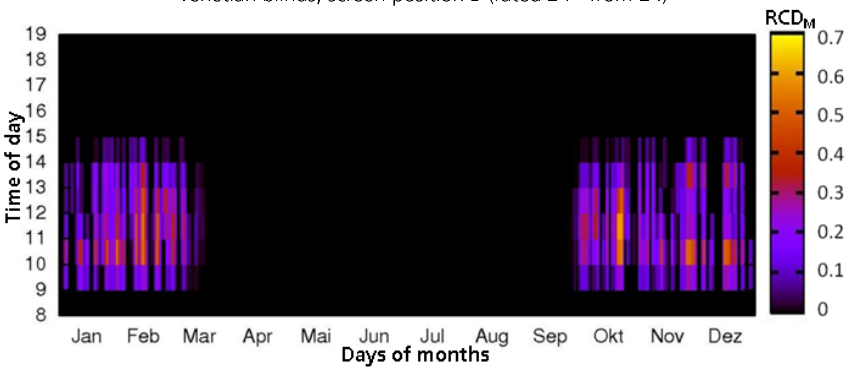


Figure 8–11: Annual veiling glare (RCD$_M$) profile of variant 1-4: fully window façade without venetian blinds; screen position 4 (rated 21th from 24).

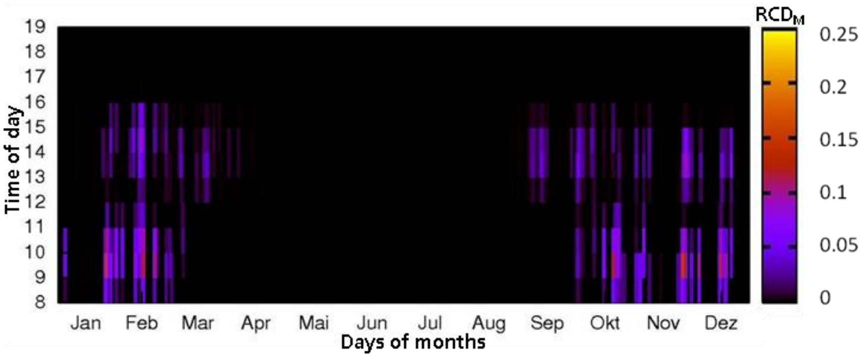


Figure 8–12: Annual veiling glare (RCD_M) profile of variant 1-5: fully window façade without venetian blinds; screen position 5 (rated 18th from 24).

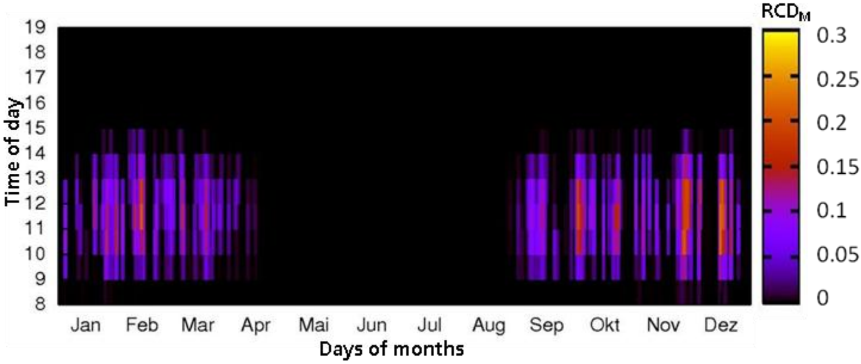


Figure 8–13: Annual veiling glare (RCD_M) profile of variant 1-6: fully window façade without venetian blinds; screen position 6 (rated 22nd from 24).

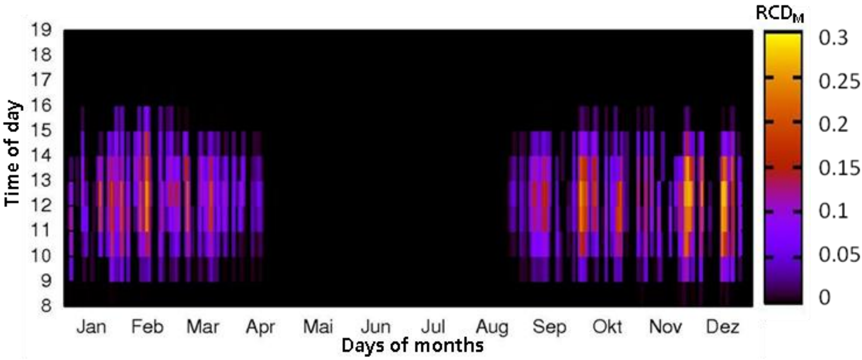


Figure 8–14: Annual veiling glare (RCD_M) profile of variant 1-7: fully window façade without venetian blinds; screen position 7 (rated 23rd from 24)

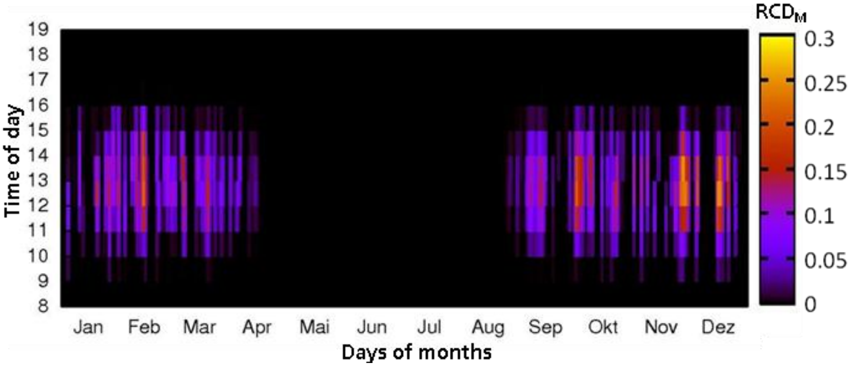


Figure 8–15: Annual veiling glare (RCD_M) profile of variant 1-8: fully window façade without venetian blinds; screen position 8 (rated 20th from 24).

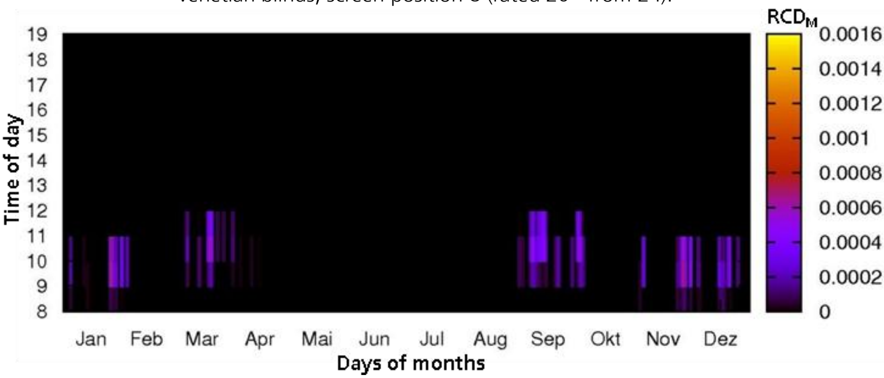


Figure 8–16: Annual veiling glare (RCD_M) profile of variant 2-1: fully window façade with venetian blinds; screen position 1(rated 6th from 24).

Figure 8–17: Annual veiling glare (RCD_M) profile of variant 2-2: fully window façade with venetian blinds; screen position 2 (rated 1st from 24).

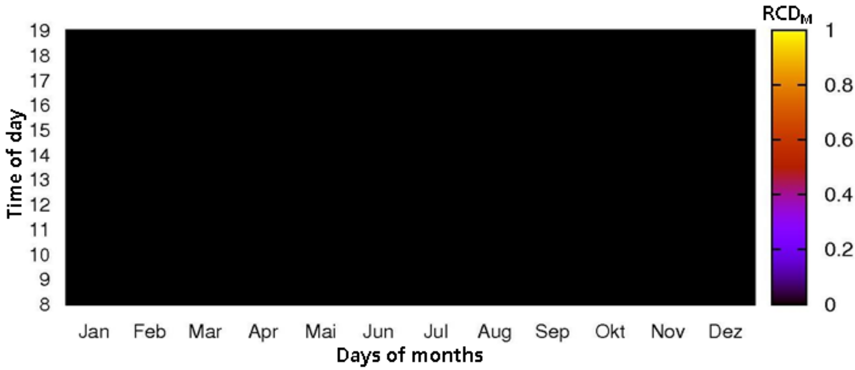


Figure 8–18: Annual veiling glare (RCD_M) profile of variant 2-3: fully window façade with venetian blinds; screen position 3 (rated 2nd from 24).

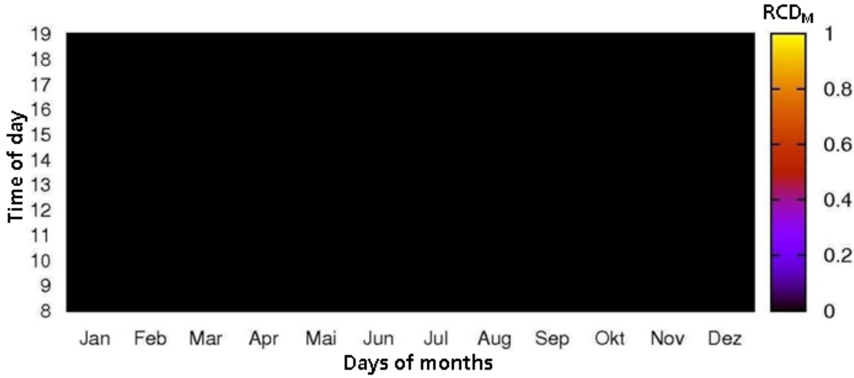


Figure 8–19: Annual veiling glare (RCD_M) profile of variant 2-4: fully window façade with venetian blinds; screen position 4 (rated 3rd from 24).

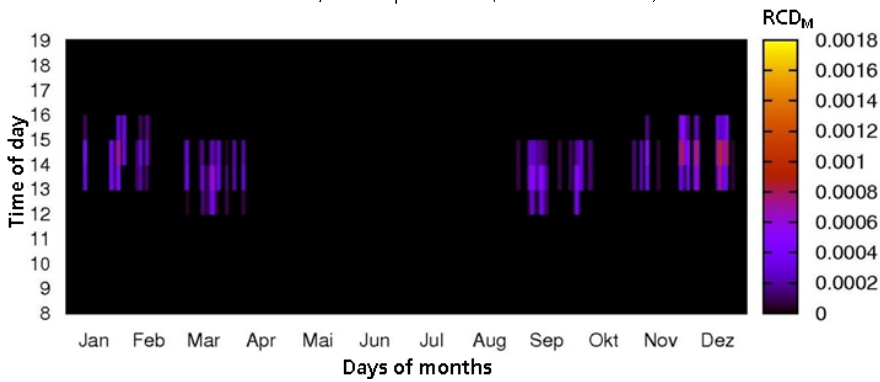


Figure 8–20: Annual veiling glare (RCD_M) profile of variant 2-5: fully window façade with venetian blinds; screen position 5 (rated 7th from 24).

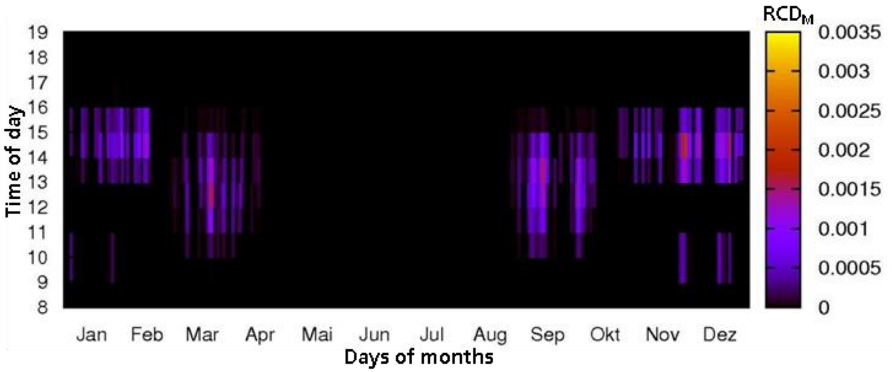


Figure 8–21: Annual veiling glare (RCD$_M$) profile of variant 2-6: fully window façade with venetian blinds; screen position 6 (rated 10th from 24).

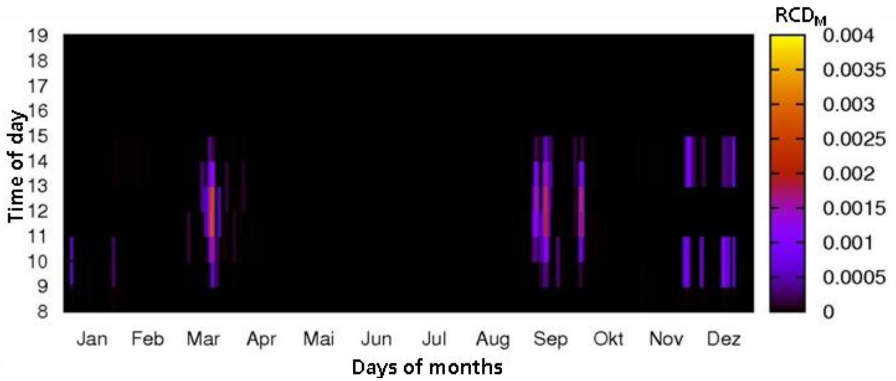


Figure 8–22: Annual veiling glare (RCD$_M$) profile of variant 2-7: fully window façade with venetian blinds; screen position 7 (rated 9th from 24).

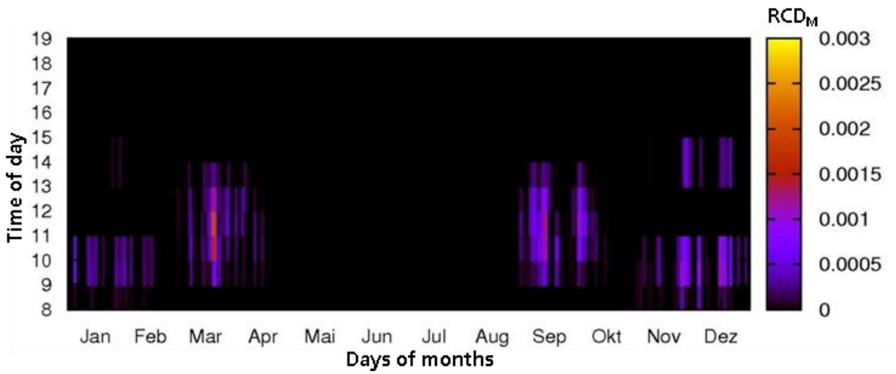


Figure 8–23: Annual veiling glare (RCD$_M$) profile of variant 2-8: fully window façade with venetian blinds; screen position 8 (rated 8th from 24).

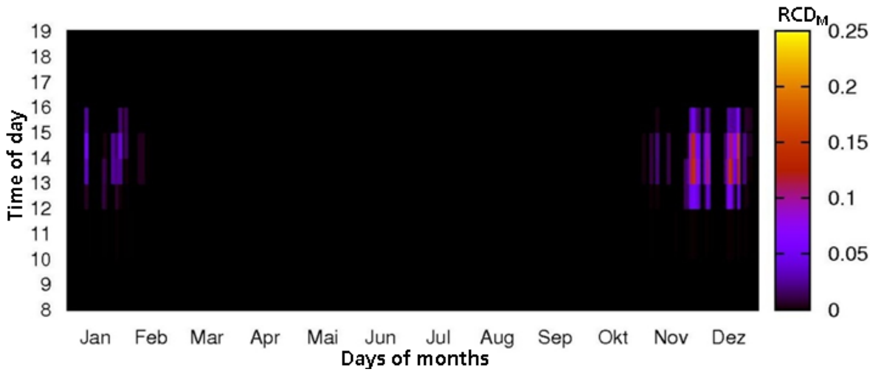


Figure 8–24: Annual veiling glare (RCD_M) profile of variant 3-1: punched window façade without venetian blinds; screen position 1 (rated 12^{th} from 24).

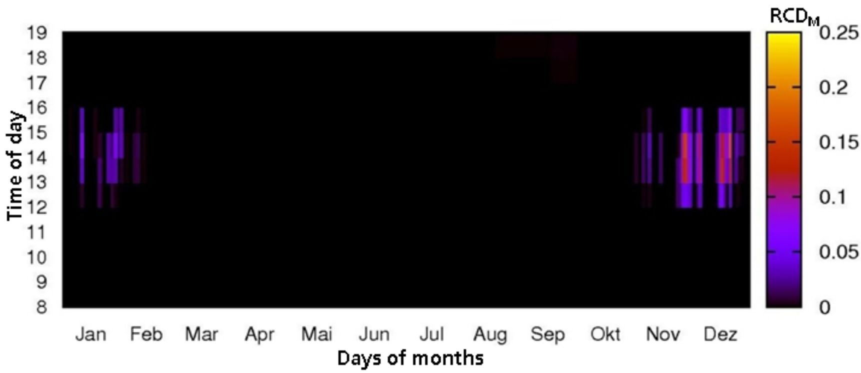


Figure 8–25: Annual veiling glare (RCD_M) profile of variant 3-2: punched window façade without venetian blinds; screen position 2 (rated 14^{th} from 24).

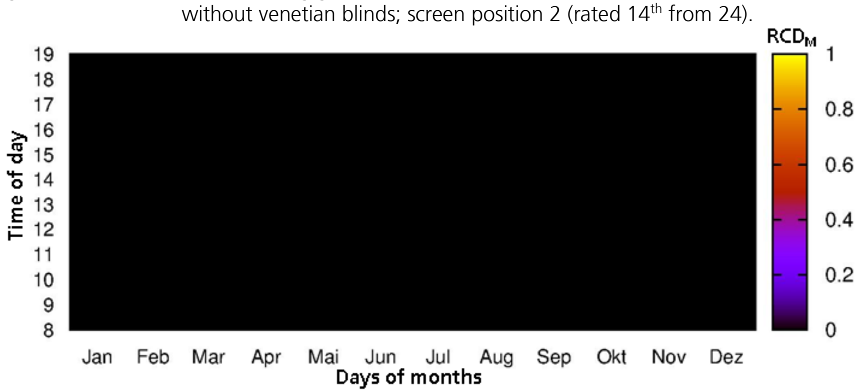


Figure 8–26: Annual veiling glare (RCD_M) profile of variant 3-3: punched window façade without venetian blinds; screen position 3 (rated 4^{th} from 24).

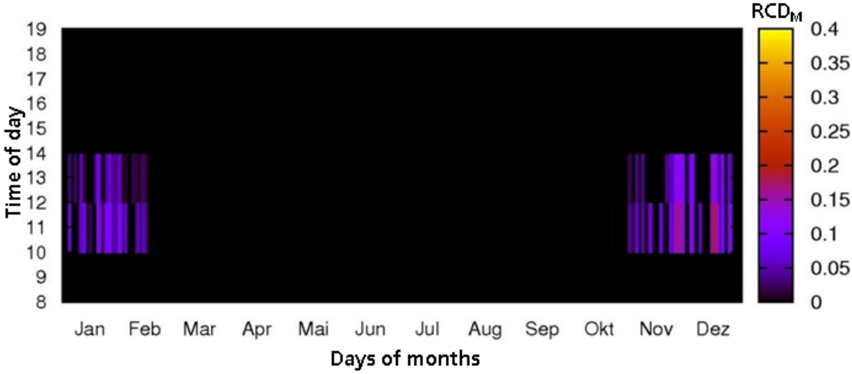


Figure 8–27: Annual veiling glare (RCD$_M$) profile of variant 3-4: punched window façade without venetian blinds; screen position 4 (rated 19th from 24).

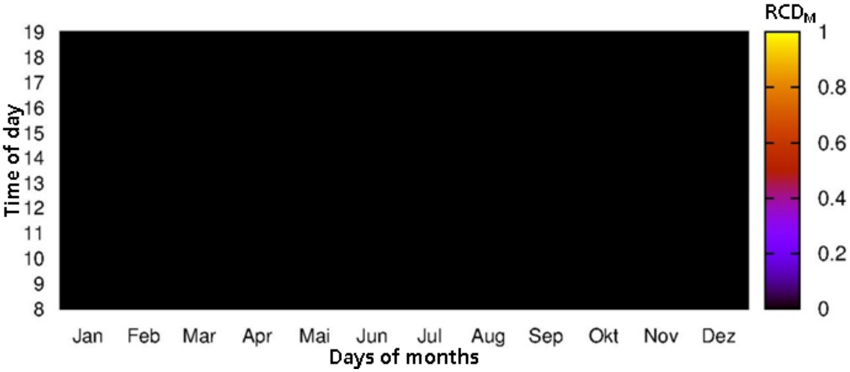


Figure 8–28: Annual veiling glare (RCD$_M$) profile of variant 3-5: punched window façade without venetian blinds; screen position 5 (rated 5th from 24).

Figure 8–29: Annual veiling glare (RCD$_M$) profile of variant 3-6: punched window façade without venetian blinds; screen position 6 (rated 15th from 24).

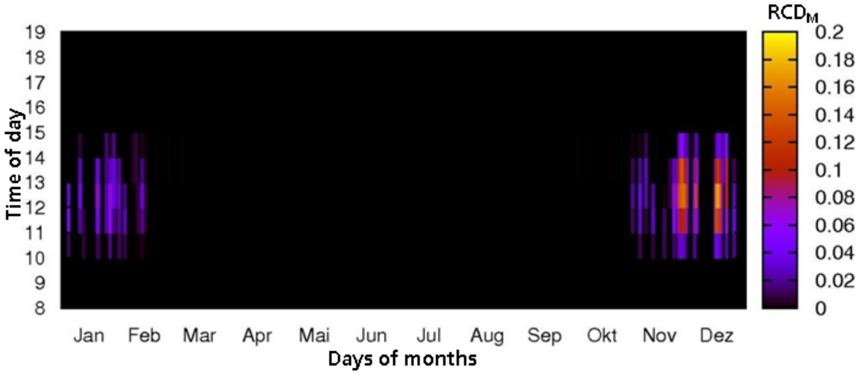


Figure 8–30: Annual veiling glare (RCD$_M$) profile of variant 3-7: punched window façade without venetian blinds; screen position 7 (rated 17th from 24).

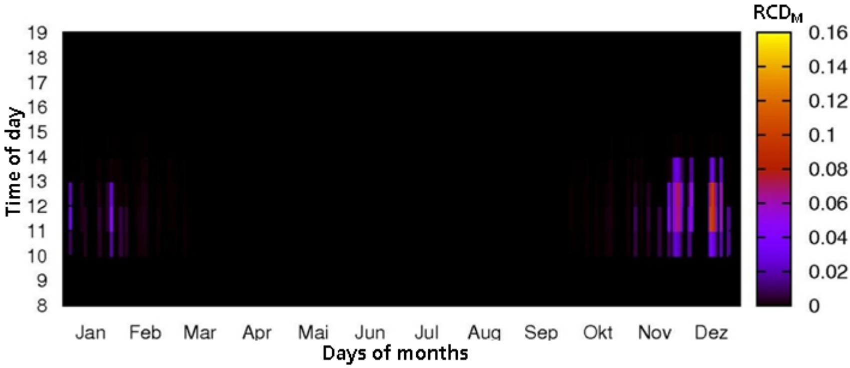


Figure 8–31: Annual veiling glare (RCD$_M$) profile of variant 3-8: punched window façade without venetian blinds; screen position 8 (rated 11th from 24).

As displayed in the above graphs for all 24 variants in an office with a south-facing window-façade and with defined geometrical and photometrical characteristics the most problematic time-zone is the period known as "winter-time" - October, November, December, January, February and March. But as demonstrated in Figure 8–16 to Figure 8–23, using venetian blinds can significantly reduce the veiling problem during this time of year. Reducing the glazing area decreases the occurrence-time of veiling glare but its effect in this regard is much less than using venetian blinds (Figure 8–24 to Figure 8–31). In order to make the possibility for a more detailed comparative study between all variants (besides the annual distributions of RCD$_M$) the average value of RCD all over the year, the maximum RCD$_M$ throughout the year, and the fraction of year with veiling glare (i.e. how much of the year (%) the screen is confronted with contrast deficiency problem) are calculated for each variant. These computed values are illustrated in Table 8-2. This evaluation helps support the possibility of comparing all variants regarding annual veiling glare in respect to average, maximum and occurrence time.

Table 8-2: Evaluation-results of all variants.

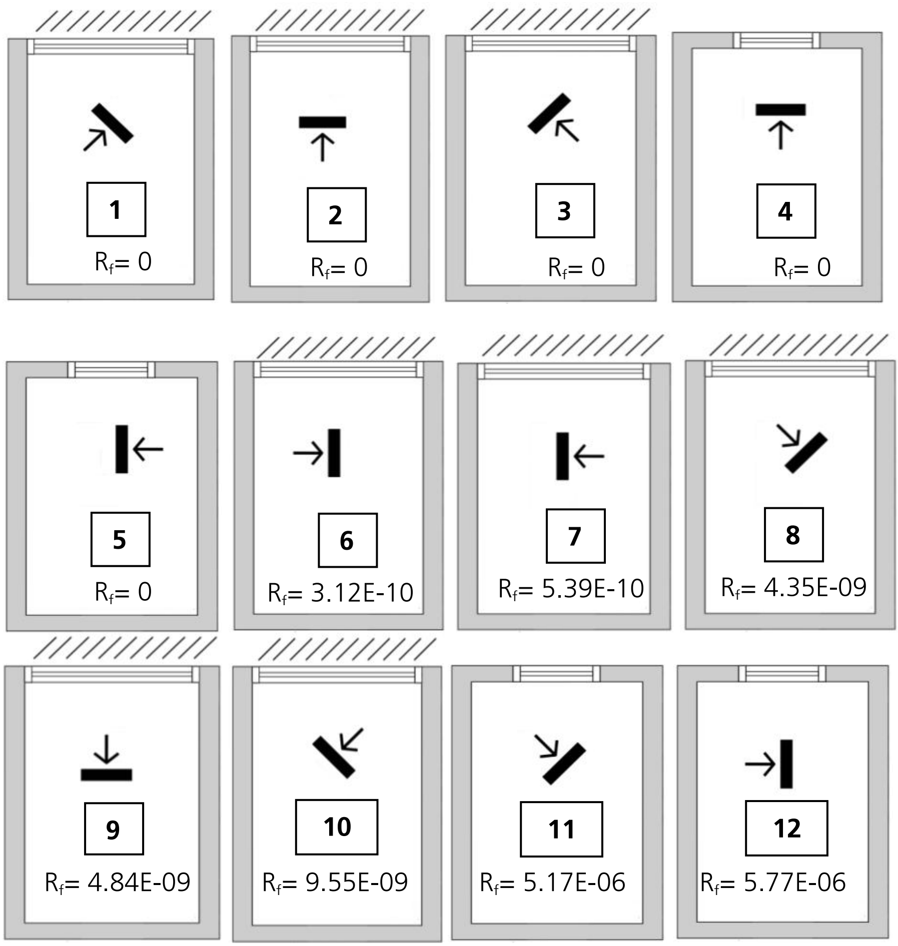
	Fraction of year with veiling glare (T_{annual})	Annual average value of RCD	Maximum value of RCD_M
Variant 1-1 (16th)	9.3%	0.0014	0.123
Variant 1-2 (13th)	3.4%	0.0014	0.15
Variant 1-3 (24th)	16.8%	0.0093	0.256
Variant 1-4 (21st)	10.3%	0.008	0.219
Variant 1-5 (18th)	13.6%	0.0016	0.104
Variant 1-6 (22nd)	18.4%	0.0072	0.187
Variant 1-7 (23rd)	17%	0.0104	0.201
Variant 1-8 (20th)	16.2%	0.0061	0.173
Variant 2-1 (6th)	2.2%	8.87E-06	0.0016
Variant 2-2 (1st)	0	0	0
Variant 2-3 (2nd)	0	0	0
Variant 2-4 (3rd)	0	0	0
Variant 2-5 (7th)	2.2%	1.36E-05	0.0018
Variant 2-6 (10th)	7%	4.4E-05	0.0031
Variant 2-7 (9th)	5%	2.69E-05	0.0036
Variant 2-8 (8th)	6%	2.9E-05	0.0025
Variant 3-1 (12th)	2.3%	0.00123	0.204
Variant 3-2 (14th)	3.3%	0.0014	0.204
Variant 3-3 (4th)	0	0	0
Variant 3-4 (19th)	2.2%	0.004	0.369
Variant 3-5 (5th)	0	0	0
Variant 3-6 (15th)	6%	0.0014	0.17
Variant 3-7 (17th)	4.6%	0.002	0.186
Variant 3-8 (11th)	5.2%	0.0007	0.142

8.3 Discussion

In order to rate the variants according to their capacity for having less veiling glare in respect to "occurrence-time", "annual average" and "maximum RCD_M" a rating factor is proposed which is a linear function of all these three factors:

$$R_f = T_{annual} \bullet RCD_{annual,average} \bullet RCD_{M,\max} \qquad (8\text{–}4)$$

According to the computed rating factor (R_f), the variants can be rated as the following image, in which number 1 is the best case with lowest value of R_f and number 24 is the worst case in respect to the veiling-glare-problem. The following illustrations are schematic images to facilitate the comparisons; the venetian blinds are in reality horizontal blinds.



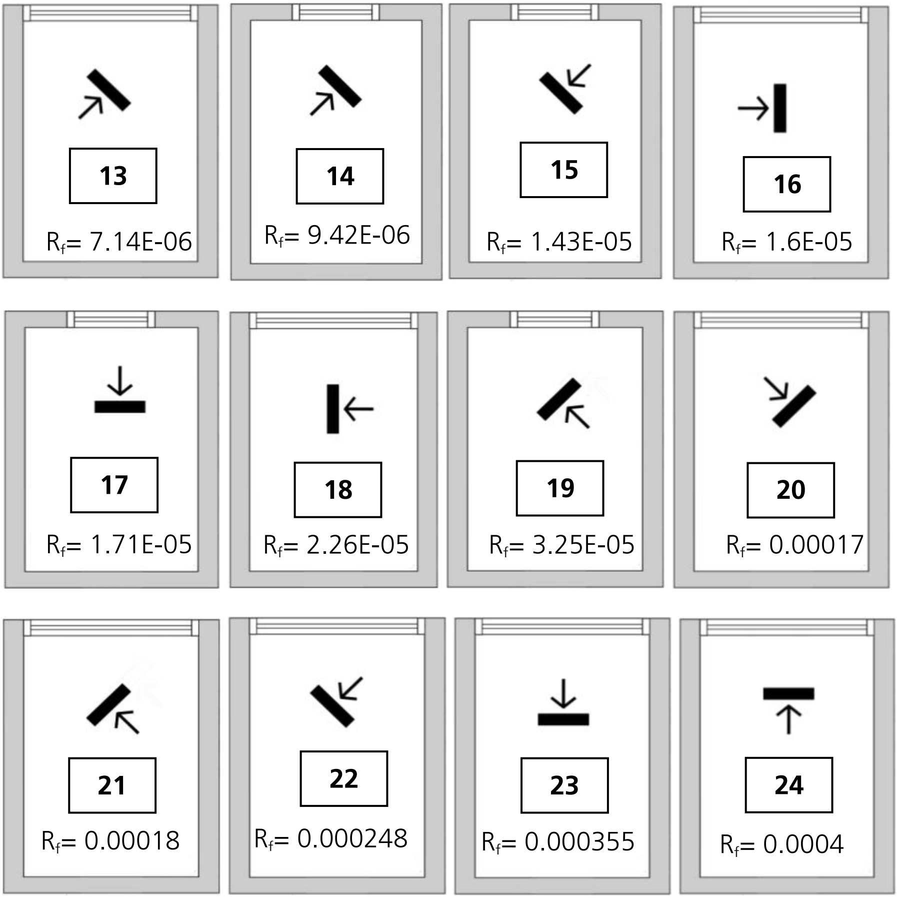


Figure 8–32: Schematic illustrations to show the ratings of all 24 variants according to their capacity for less veiling glare problem. Number 1 to 5 are the best variants with R_f=0; this means in this rating system there is no difference between the rated variants 1st to 5th from 24.

The conclusions of this evaluation can be summarized as:

- The most problematic year-period is the time between October and March, especially for the cases with large window size and without venetian blinds.
- The variants with venetian blinds are in general the best options with less veiling-glare problems.
- Reducing the glazing area has less influence on reducing veiling glare than applying a shading system such as venetian blinds.
- The best VDT orientation relative to windows is dependent on the

window size and shading system and it is not possible to highlight one orientation as the absolute best orientation.

It must be taken into consideration that these outcomes are valid for a south facing office room with the certain geometrical and photometrical properties with the described visual display and located in the mentioned geographical situation. The conclusions cannot be used as a standard or be generalized for other cases with different properties. To create standards for placing the visual displays inside the rooms it is necessary to make a broader study in this regard and perform many simulations with many different VDT locations, room layout and geographical locations to have enough material for generating appropriate rules. In conclusion, in order to decide the best location for a visual display in a room (in respect of its legibility), the current suggestion would be to conduct annual simulations for all possible variants to choose the best one.

8.4 Automated procedure

In order to alleviate the above mentioned procedure which is implemented in different steps and by using several programs, a computer-based tool is developed which makes the whole process possible via configuration and running a script. This tool is programmed by C++ and includes two major parts[25]:

- **Part1, RADIANCE-based:** this part is based on the RADIANCE program and can be used in order to generate the veiling-glare profile of a visual display under a single lighting condition. To install and apply this tool it is required to install the RADIANCE program first. This part of the developed tool is called “gen_vf”.
- **Part 2, DAYSIM-based:** this part is based on both the RADIANCE and DAYSIM programs and can be used to generate the veiling-glare profile of a visual display throughout the year in defined time steps. To install and apply this tool it is necessary to firstly install both RADIANCE and DAYSIM. This part of the developed tool is called “gen_vfd”.

Appendix G includes some descriptions about the input data and output files of both developed “gen_vf” and “gen_vfd”.

8.5 Conclusion

The within this research developed MRC model has been implemented in the lighting simulation programs, RADIANCE and DAYSIM; and a simulation based

[25] Development of this tool was assign to Augustinus Topor; he is very much appreciated for the kind co-operation and his contribution to this research study.

method has been developed which facilitates the prediction of annual veiling glare on computer screens in any space. This method is the final step in realizing the purpose of this Ph.D. thesis which was the development of a method to evaluate screen related visual quality in office spaces.

The developed method can be used in the design phase of the spaces including visual displays in order to prevent conditions with a potential excessive veiling glare problem. Although by changing the location of a visual display in a room, it is sometimes possible to eliminate veiling glare but certain spaces do not permit this flexibility. Therefore, in the design strategy (with relation to veiling glare) the flexibility level of the users for adjusting their display position should also be considered.

In reality veiling glare should be considered in the design phase of a space as well as other factors such as discomfort glare, adequate illuminance, daylight factor and visual contact to outside, in order to improve the quality of the space in a wide range. However, the described example in this chapter is merely an evaluation base on veiling glare excluding other important factors which should be considered in the design strategy. For instance one variant might be good according to veiling glare but does not provide sufficient illuminance at the work place or could be inappropriate due to discomfort glare or view contact. Therefore, in order to necessitate a high quality design all of the significant factors should be taken into account and the final decision should be made based on a good compromise between all criteria.

8.6 Outlook for further developments

The developed method and application tool could be used as an aiding tool for improving the design of spaces with onscreen visual tasks e.g. office spaces, conference rooms and public places like airports.

In the case of office spaces performing a sufficient amount of simulation could provide the following outcomes:

- Regulations regarding proper angles of visual display relative to window, based on the type, size and orientation of the window façade (improving existing suggestions or proposing new suggestions).
- Categorizing different shading systems in respect to their effectiveness in reducing veiling glare.
- Categorizing of different office layouts in respect to their potential for a good screen-legibility with low veiling glare.

In case of public places enclosing visual displays like airports, main stations and social places with a public screen (for watching news or sports) a different type of visual display called public displays comes into consideration. The main distinctive point of public displays from other displays is the number of viewpoints. These types of visual displays might be confronted with a significant visibility problem due to various view points and view directions.

The application tool developed within the scope of this research study is mainly intended for individual display usage which is considered only for a single viewpoint. In order to apply this tool to evaluate public displays it is necessary to repeat the simulations for many different viewpoints and then evaluate the results separately by averaging them or weighting them according to the importance of different view directions. This procedure would be extremely time consuming and therefore impractical. One important outlook for the further development in this regard is modifying the developed tool and generating a new version compatible with public displays. This modification would mainly involve the input of viewpoint by changing it from a single viewpoint to a number of viewpoints with an additional weighting function to consider the effect of the viewpoints distribution. Applying this modified tool to public visual displays could result in the following outcomes:

- The best location for placement of the screen in the public-space, to provide best possible visibility from all potential viewpoints.
- The best declination angle of the screen which could also be automatically controlled by a motorized system; this system should be programmed according to the estimated veiling glare as a function of lighting condition and viewpoints' distribution order.

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10 List of symbols

B_L:	Background luminance of the display [cd/m^2]
BRDF:	Bidirectional reflectance distribution function
CD:	Contrast deficiency [-]
CI:	Comfort index [-]
CGI	CIE glare index
CR:	Contrast ratio [-]
CR_1:	Initial contrast ratio excluding reflection
CR_{min}:	Minimum required contrast [-]
$\overline{C}$:	Contrast threshold [-]
DGI	Daylight glare index
DGP	Daylight glare probability
Dist:	Distance between viewpoint and screen
d_t :	Threshold gap size [minute of arc]
D_{vf}:	Dimension of view field (considered unit area in figure 7-7)
D_{view}:	Distance from the display [mm]
E	Illuminance [lux]
E_{glare}:	Illuminance at the eye caused by glare source [lux]
E_v:	Vertical eye illuminance [lux]
$E(\theta_r, \varphi_r)$:	Illuminance of the light incident on the sample from the direction (θ_i, φ_i)
K_{age}:	Age multiplier [-]
L_b:	Luminance of image background [cd/m^2]
L_{black}:	Luminance of black text [cd/m²]
L_C:	Luminance of Landolt ring [cd/m^2]
L_E:	Average environment Luminance [cd/m^2]
L_g:	Luminance of glare source [cd/m^2]
$L_{H,1}$:	Initial luminance of bright part excluding reflection [cd/m^2]
L_H:	High state luminance [cd/m²]
$L_{L,1}$:	Initial luminance of dark part excluding reflection [cd/m^2]
L_L:	Low state luminance [cd/m²]
L_r:	Reflection luminance [cd/m²]
L_s:	Luminance of glare source [cd/m²]
L_v:	Veiling luminance over the retinal area [cd/m^2]
L_{veil}:	Veiling luminance over the retinal area [cd/m^2]
L_{white}:	Luminance of white background [cd/m²]
$L(\theta_i, \varphi_i)$:	Reflected luminance measured from the direction of (θ_r, φ_r)
MRC:	Minimum required contrast
$N_{H, Height}$:	Height in pixel
P:	Position index [-]

P_A:	Peak of simulated BRDF of Material A for incident angle of 30°
P_B:	Peak of simulated BRDF of Material B for incident angle of 70°
PI:	Polarity index [-]
PF_i:	Estimated peak factor of modeled BRDF for incident angle θi
$P_{M,i}$:	Peak of measured BRDF for incident angle θi
RCD:	Relative contrast deficiency to express veiling glare magnitude
$RCD_{annual, average}$:	Average annual RCD
$RCD_{M, max}$:	Maximum RCD_M throughout the year
RCD_M:	RCD value averaged for the whole screen area
RD:	Diffuse part of reflectance measured by integrating sphere
R_f:	Rating factor
R_H:	Hemispherical reflectance measured by integrating sphere
rRMSE:	Relative root mean square error
T_{annual}:	Fraction of year with veiling glare
$TC_{non-std}$:	Non standard threshold contrast
TC_{std}:	Standard threshold contrast
VA:	Visual acuity
VF:	Veiling factor [-]
V_{Pitch}:	Height of a pixel [mm]
α:	Angular size of visual target [minute of arc]
β:	Angle between glare source and the line of sight [degree]
$\rho_{ceiling}$:	Total reflectance of ceiling in visible spectrum
ρ_{desk}:	Total reflectance of desk in visible spectrum
ρ_{floor}:	Total reflectance of floor in visible spectrum
ρ_{vis}:	Total reflectance in visible spectrum
ρ_{wall}:	Total reflectance of wall in visible spectrum
Ψ:	Character height [minute of arc]
Ω_{in};	Solid angle light beam in gonio-Photometer measurement
Ω_{out};	Solid angle of detector in gonio-Photometer measurement
θ_i,ϕ_i:	Altitude and azimuth angle of incoming light incident on the sample
θ_r,ϕ_r:	Altitude and azimuth angle of reflected light from the sample
$\vec{x}_{out}$	Outgoing directions, from the sample to the detector in Gonio-Photometer measurement
$\vec{x}_{in}$	Incoming directions, from the light to the sample in Gonio-Photometer measurement
ω_s:	Solid angle of source [str]

11 Appendix A: Corresponding part of ECCO-build questionnaire

This is a small part of the questionnaire that has been used for the user assessments in the project "Energy and Comfort Control for Building management systems" the whole questionnaire is available from [18]. This is the corresponding part, translated in English, including the question (highlighted with red lines) which is used for the described evolutions in chapter-3 (see Figure 3–8)

Part 2B. Questions about the lighting conditions when typing text

2.1 How do you rate the current *light level* when typing the text?

	Too low	Too high
The light level on the keyboard		
The light level on the screen		

2.2 How satisfied are you with the current *light level* for typing the text?

	Very satisfied	Very dissatisfied
The light level on the keyboard		
The light level on the screen		

2.3 When typing the text, where you bothered by

	Not at all	Very much
Glare from window		
Glare off shading device		
Reflections on the screen		

2.4 When typing the text, please mark the degree of glare you experienced from the window and the shading device

	Imperceptible	Noticeable	Disturbing	Intolerable
Window	☐	☐	☐	☐
Shading device	☐	☐	☐	☐

12 Appendix B: Corresponding part of QUANTA questionnaire

This is one part of the questionnaire that was used for the user assessments in the QUANTA project (see 1.4-Background of the Thesis) the corresponding questions used for the mentioned evaluations in chapter-4 (see Figure 4–15 and Figure 4–16) are translated into English and highlighted with red lines.

Questions about the lighting conditions when typing text

Nehmen Sie Sich für diesen Teil bitte die nötige Zeit! Lassen Sie die Beleuchtungssituation etwas auf Sich wirken.

3.2.1 Haben Sie „blind" geschrieben, ohne auf die Tastatur zu sehen?

☐ Ja, ich habe blind geschrieben

☐ Nein, ich habe auf die Tastatur gesehen

3.2.2 Bewerten Sie bitte den <u>Bildschirm</u> an dem Sie gerade gearbeitet haben bezüglich der visuellen Qualität.

	Schlecht	Exzellent
Der Bildschirm ist		
Der Kontrast zwischen Bildschirm und Umgebung ist		

3.2.3 How do you estimate the current lighting level for typing a text on PC?

	Very low	Very high
The lighting level on the keyboard is		
The lighting level on the screen is		

3.2.4 When you typed the text, were you bothered via …?

	Not at all	Very much
Glare from window and/or shading system		
Reflection on the screen		

3.2.5 Bitte markieren Sie den Grad der Blendung durch Fenster und Verschattungseinrichtung, den Sie während der Schreibaufgabe empfanden.

Nicht wahrnehmbar	Wahrnehmbar	Störend	Nicht tolerierbar
☐	☐	☐	☐

3.2.6 Nehmen Sie an, Sie müssten ihre tägliche Schreibarbeit an diesem Arbeitsplatz verrichten. Die <u>Beleuchtungssituation</u> ist dazu...

Eindeutig komfortabel

Gerade komfortabel

Gerade unkomfortabel

ndeutig unkomfortabel

13 Appendix C: Introduction for the subjects

This introduction was given to the test persons before starting the test procedure explained in chapter 5.

Introduction The test consists of four parts: Each part of test must be started by switching the corresponding button or by the help of experimenter. The relevant parts are described in more details in the following.	
1	The first part will be conducted by the experimenter. Please follow the instruction
Pause	
2	In the second part a text appears on the screen Please press the blue button to start. Note: Please note that the test starts immediately after pressing the button. Please read the text aloud, and as quickly and accurately as you can. Try to avoid mistakes.
Pause	
3	The third part will be conducted by the experimenter. Note: Please note that the test starts immediately after pressing the button. Please read the text aloud, and as quickly and accurately as you can. Try to avoid mistakes.
4	In the fourth part again a text appears on the screen Please press the orange button to start. Note: Please note that the test starts immediately after pressing the button. Please read the text aloud, and as quickly and accurately as you can. Try to avoid mistakes. Please note that the test starts immediately after pressing the button. After each text, a rating scale appears. Please give your opinion on how comfortable the reading task was for you, by pressing the corresponding keys on the keyboard. **Comfort to read** **Readable but not comfortable** **Unreadable** **Next** →
Part 5 and 6 are similar to 3 and 4 with white text on black screen	
5 Minuts break	
After the break, part 3 to 6 are repeated under daylight condition	

14 Appendix D: An example of a fair copy

This is an example of the fair copy prepared for reading acuity test. The experimenter marks the unread or incorrectly read words out on the fair copy.

Reading Acuity			
1	20sec	6	4sec
rot elf Pate geht fünfzig Mai sehr Morgen mir einmal nur Winter Säule August Weg sonnig		dritte zwei zehn Sonntag nie Juli sechs Mai zählen ganz einmal lila Strahl Kuh steht	
2	14sec	7	3sec
violett ihr Abend tun Herbst Punkt achte sie neunte zweite Uhr Mäuse Hälfte uns Monat		Tag rot Kuh froh Fahrrad aus Zahl Monat uns Hälfte tun Herbst Tröge violett ihr Abend	
3	10sec	8	2sec
sie man wir drei siebzig Uhr eins sonnig Weg Mäuse Tag sieben Alter vierte Ehe zwölf		zählen Mai sechs schwarz ihm grau Schuh nun rühren heiß zehnte gelb Hälfte uns Monat	
4	8sec	9	1sec
Weg Tag Sie fünf neunzig Ehe drei Osten tun Herbst Tod dritte Kiste neunte sie achte		vierte Ehe zwölf Februar tun Zeit acht Baum sieben hält orange weiß rühren nun Schuh	
5	6sec		
wem ich mal vier achtzig Tod zwei Süden nie Sommer Eule zweite eins fünfte ich erste			

15 Appendix E: Gonio-photometer

The gonio-photometer used for these measurements has been designed and built by Peter Apian-Bennewitz during his Diploma Thesis [9] and his Ph.D. [11] and is currently available in the laboratory of the Fraunhofer Institute ISE. This is "an apparatus for measuring angle-dependent transmission and reflection of large (40x40cm) samples. The apparatus consists of two fixed light sources, an adjustable sample holder and a movable solar cell as the detector. All angle positions are computer-controlled using a workstation to achieve automatic measurements."10] The detector and sample holder are movable in both altitude and azimuth directions. For starting the measurements the computer screen is fixed in the sample holder and one of the two light sources is used as incident light beam and the device is set up to perform the measurement every 10 degree in altitude direction and every 45 degree in azimuth direction. The reflected light for each incident angle are measured in fine intervals of less than one degree throughout the whole hemisphere. Around the specular angle of reflection the measurements that are made are even finer by up to 0.1 degree. Because of device restrictions due to the self shading problem measurement of all incident angles is not possible; our measurements are made for the altitude incident angles between 30 to 70 degrees. The following image illustrates a schematic shape of the gonio-photometer used for the measurements in this study.

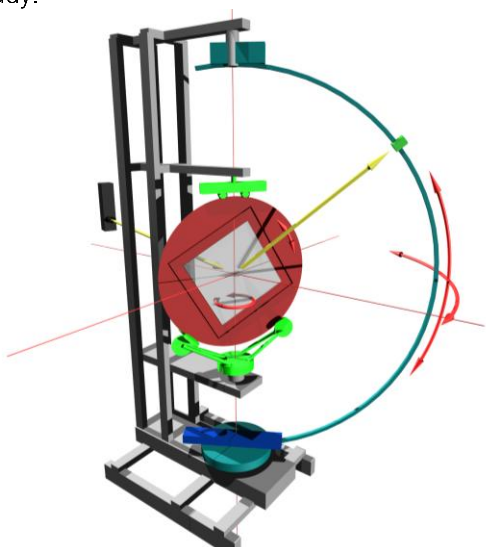

Figure 15–1: A schematic image of the gonio-photometer[26].

[26] Peter Apian Bennewitz is thanked for providing the author with this image

Figure 15–2 shows the polar coordination system centered about the sample with respective incoming and outgoing directions which are symbolized as:

θ_i, φ_i: altitude and azimuth angle of incoming light incident on sample

θ_i, φ_i: altitude and azimuth angle of reflected light ray from the sample

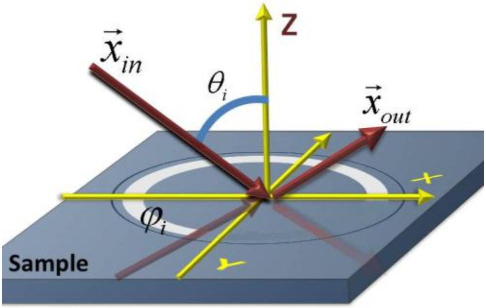

Figure 15–2: Coordinate system centered on the sample normal (z axis) showing the light beam incident on and reflected from the sample.

The measurements are conducted once for the reflected light from the sample to achieve the reflected luminance value at different directions, and once for the light beam without a sample to derive the illuminance value of the beam. These measurements are finally applied to calculate the BRDF values of the sample. By consideration of $\vec{x}_{in}$, $\vec{x}_{out}$ as incoming and outgoing directions, from the light to the sample and from the sample to the detector, the measured BRDF is averaged over solid angles of the detector $\Delta\Omega_{out}$ and the light beam $\Delta\Omega_{in}$ [8]:

$$BRDF(\Delta\Omega_{in}, \Delta\Omega_{out}) = \frac{1}{\Delta\Omega_{in}, \Delta\Omega_{out}} \int_{\vec{x}_{out}}^{\Delta\Omega_{out}} \int_{\vec{x}_{in}}^{\Delta\Omega_{in}} BRDF(\vec{x}_{out}, \vec{x}_{in}) d\Omega_{in} d\Omega_{out} \quad (15–1)$$

Since the light source is relatively far away from the sample the incoming light to the sample is assumed to be parallel. The BRDF by this assumption can be described with the following formula:

$$BRDF(\theta_i, \varphi_i, \theta_r, \varphi_r) \approx \frac{L(\theta_r, \varphi_r)}{E(\theta_i, \varphi_i)} \quad (15–2)$$

$L(\theta_r, \varphi_r)$: reflected luminance measured from the direction of (θ_r, φ_r)

$E(\theta_i, \varphi_i)$: illuminance of the light incident on the sample from direction (θ_i, φ_i)

This equation is applied to calculate the BRDF values in the current study.

16 Appendix F: Integrating sphere

The normal-hemispherical and normal-diffuse reflectance measurements of the monitor surface are implemented with a Lambda-900 double-beam spectrometer. The integrating sphere[27] of the Lambda-900 spectrometer has a diameter of 220 mm (see Figure 16–1). The normal-hemispherical reflectance measurements with the Lambda-900 spectrometer and the integrating sphere are conducted using a TNO-calibrated, back-surface aluminum mirror / a PTB-calibrated white standard made of sintered PTFE as the reference. The transmittance and reflectance apertures in the 220 mm integrating sphere each have a diameter of 25 mm. The beam is incident on the sample with an angle of 8 ° for normal-hemispherical and normal-diffuse reflectance measurements.

[27] The 220 mm integrating sphere has been designed and produced in collaboration between Fraunhofer institute of solar energy systems and Perkin Elmer manufacturer.

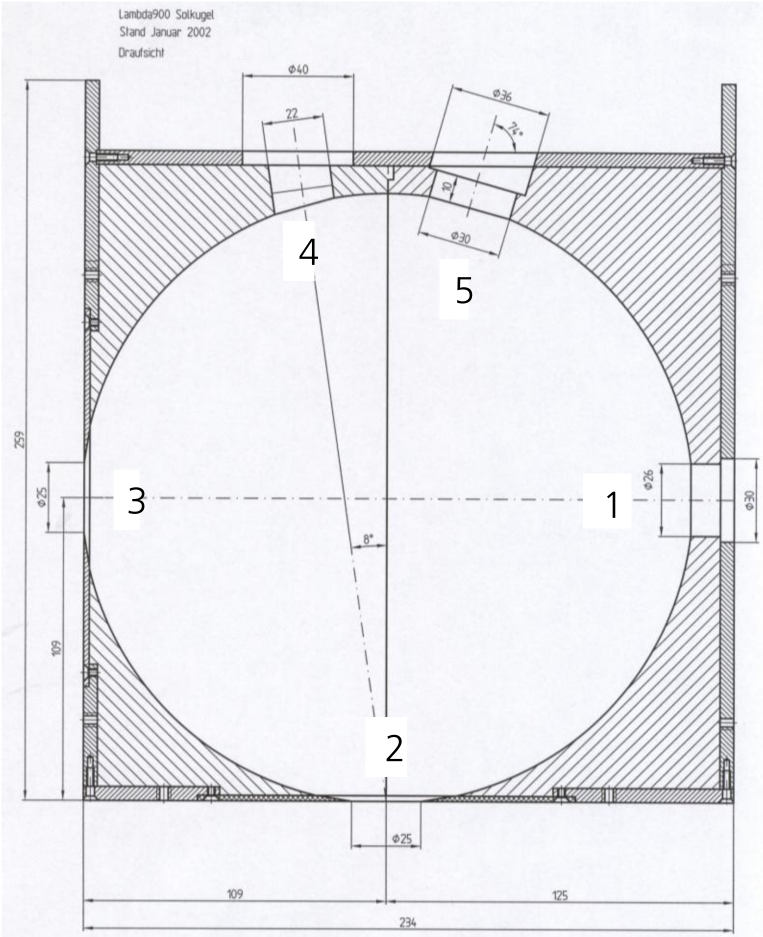

Figure 16–1: Horizontal cross-section through the integrating sphere to determine the normal-hemispherical and normal-diffuse transmittance and reflectance. For reflectance measurements the sample is placed at port 2; the reference beam enters via port 3; the sample beam enters via port 4. The „gloss trap" is located at port 5 for normal-diffuse reflectance measurements. The beam is incident on the sample with an angle of 8 ° for reflectance measurements.[28]

[28] The descriptions of integrating sphere and the respective image have been adopted from an ISE-intern report "Spectral measurements of a sample and calculations of light and solar energy values" prepared by Helen Rose Wilson. Helen Rose Wilson is thanked for her contribution with providing the author with this information.

17 Appendix G: Input and output files of the developed tool

17.1 Input data

The following files shall be given to the tool in order to start the simulation. The name and the path to the files shall be stated in the configuration-file. The format of the geometry and material files is similar to the RADIANCE file-format.

- A weather dataset from the location of the simulated building based on hourly values; this dataset is similar to the weather data used for DAYSIM simulation and can be generated by means of the program Meteonorm 48. This file is used for annual simulation by "gen_vfd".
- A material file of the whole scene apart from visual display.
- A geometry file which contains the whole scene is to be simulated separately from the visual display.
- The geometry file of the visual display. The display plane must be in the XZ-plane of the coordination system with the normal facing towards the negative Y-axis. The center of the monitor must be at (0, 0, 0).
- The material file of the visual display in on state;
- The material file of visual display in off state.

The read-in information which shall be given to the tool through the configuration file (header file) and reads as follows:

- Viewpoint of the user which can be specified in one of following three methods:
    - o Absolute viewpoint given by coordination (x, y, z) of the view point.
    - o Viewpoint relative to the center point of the visual display given in coordination format (x, y, z).
    - o Viewpoint relative to the position of visual display given by:
        - distance to the centre of the screen
        - view angle relative to the screen normal(+=up)
- Position of the monitor according to which the screen will be moved and/or rotated to be placed in the scene; this would be given by:
    - o Coordination of the screen centre
    - o Normal to the screen

17.2 Output

The outputs of the "gen_vf" and "gen_vfd" i.e. the developed tool for single simulation and annual simulation are:

- A contrast-file including the coordination of the viewpoints and view directions and contrast ratio between any two adjacent areas.

- A MRC-file including the coordination of the viewpoints and view directions and MRC between any two adjacent areas.
- A problem-file including the coordination of the view points, view directions and relative contrast deficiency (RCD).

In the case of “gen_vf”, these files include the computed data at a predetermined time and in the case of “gen_vfd”, each output-file is a matrix of the mentioned data at all defined time steps throughout the year.