SIMULATION AND OPTIMISATION OF COCKPIT DISPLAY VISIBILITY

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OVERVIEW

The use of displays is increasing in modern cockpits. Improved size, resolution, colour quality and affordability lead the way to new product ranges. Unfortunately, larger displays and higher resolutions tempt content designers to overflow these devices with information, thus offering users more data than they are capable of processing. Especially unsuitable presentation formats and bad contrast-ratios diminish readability and comprehensibility of displays. The aircraft cockpit is an example, where unsuitable display design can cause misinterpretations and fatal accidents. During the development of aircraft cockpits, it is indispensable to identify the visibility and readability of display configurations at an early stage. Using lighting simulations, it is possible to anticipate, analyse and plan these qualities within a virtual product. A simulation model for the Contrast Threshold is developed in consideration of relevant parameters such as adaptation luminance, target size, exposure time, contrast polarity and observer age. This model is subsequently validated through experiments and integrated into an existing display assessment method for the aviation industry with the aid of adequate visualisation methods. Eventually, the method is applied to an industrial case.

1. INTRODUCTION

Modern aircraft are equipped with so-called “glass cockpits”, which refers to the fact that obsolete scale instruments have been replaced by liquid crystal displays (LCD). These user interface devices provide the system designer with a great variety of possible display layouts and data representations. In order to assess the quality of different display layouts, a method for simulating the human perception of display contents was developed and is presented here. In combination with lighting simulations the quantitative readability of alphanumeric screen objects can be determined for a cockpit layout that exists only as a CAD model. Due to the long life cycles of aircraft and the high development costs, future aircraft will be designed, simulated and evaluated in virtual environments, so this method focuses on the rating of virtual prototypes' displays. The quality and accuracy of lighting simulations has now reached a level that makes them indistinguishable from real world measurings [1].

2. VISIBILITY COMPUTATION

Human perception is a very wide field. Science is still far away from understanding all principles of human sensing and processing. However, certain elements of human perception are well-understood and documented, for example the perception of contrasts, which is crucial for discriminating alphanumeric symbols on displays. This knowledge is obtained by using psychophysical methods, which means that physical stimuli are experimentally related to psychological responses.

In the following section, a method for contrast perception simulation based upon psychophysical experiments will be presented.

2.1. Contrast Threshold

One of the above mentioned psychophysical relations is described by the Weber-Fechner-Law [2]:

(1) $$E = k \cdot \log \frac{\Delta I}{I}.$$

It states that the difference between the intensity of a sensory stimulus *ΔI* and the reference stimulus *I* must have a constant proportional share to be perceptible (*k* being a constant, *E* being the sensation).

In terms of luminance, which is the perceived brightness, this results in the Contrast *C*, which is the difference between foreground and background luminance, divided by the background luminance.

(2) $$C = \frac{\Delta L}{L} = \frac{L_{foreground} - L_{background}}{L_{background}}$$

The higher the contrast *C*, the better one can discriminate foreground and background. If the contrast is reduced, one will sooner or later arrive at the Contrast Threshold C_{th}. The Contrast Threshold is defined as the contrast that has a detection probability of 50% in experiments. C_{th} is a function of different parameters, which will be described later.

In daily life, luminances from 10^{-6} to 10^{8} cd/m² hit the eye [3]. In order to cope with these 14 orders of magnitude, the eye and its receptors can shift their sensitivity to adjust to different environmental conditions. This process is called adaptation and is caused by the actual luminance, which is called Adaptation Luminance L_a. One will notice this effect when leaving a bright sun-lit street and entering a dark theatre. In the first seconds one will probably be blinded, and after a couple of minutes sight will recover, improving during the next thirty minutes. When leaving the theatre and entering the street, again, everything will be too bright, and one will have to wait until the eyes have adapted to the new environmental conditions. The only difference to the dark-adaptation is the time factor: light-adaptation is completed in a couple of seconds, not minutes.

So, Adaptation Luminance has a strong influence on the human vision function, not only in the transient state, but also in the stationary condition. L_a is the main influence on C_{th}.

Prof. Adrian collected numerous publications and compiled them into one unified perceptual model for computing the Threshold Contrast C_{th} [4]:

(3)

$$\Delta L_{th} = 2.6 \cdot \left(\frac{\varphi^{0.5}}{\alpha} + L_f^{0.5} \right) \cdot F_{CP} \cdot \frac{a(L_a, \alpha) + \Delta t}{\Delta t} \cdot AF$$

The Threshold Luminance depends on the four functions Target size (α, φ, L_f), Contrast Polarity F_{CP} , Exposure Time Δt and Age factor AF.

2.1.1. Size

Symbol readability depends enormously on the symbol's size. Obviously, large symbols offer a higher readability. The above mentioned factor describes the quantitative influence of symbol size (α) on the Contrast Threshold. Figure 1 shows the gradient of the Contrast Threshold in relation to symbol size at an Adaptation Luminance of 1000 cd/m². Different Adaptation Luminances would of course cause different characteristics of this curve. The figure shows two areas of impact. The right area denominates the Weber law, where the symbol size is large enough to not have an effect on readability anymore. For smaller α the Weber law is replaced by Ricco's law for spatial summation. It can be seen clearly that very small symbol sizes α will lead to an increased threshold luminance, which consequently means a higher Contrast Threshold C_{th}. φ and L_f are functions of the background Luminance or Adaptation Luminance L_a, which take day and night adaptation into consideration.

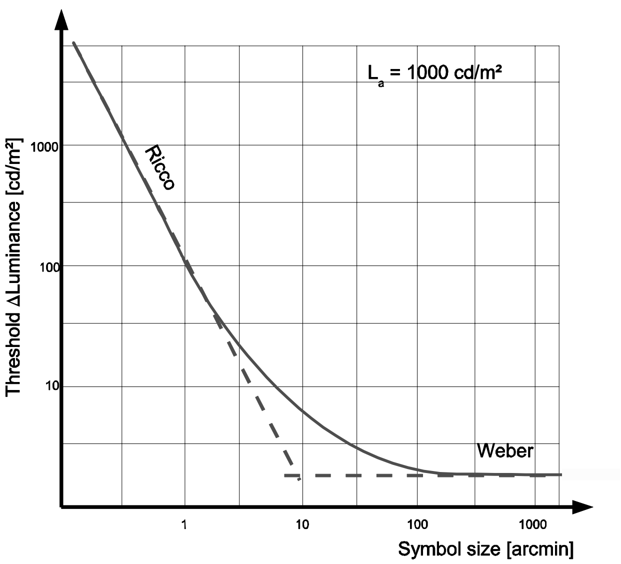

Figure 1: Influence of symbol size on Contrast Threshold [4]

2.1.2. Contrast Polarity

Contrast Polarity F_{CP} describes the relation between foreground and background luminance, i.e. light foreground on dark background or vice versa. A positive F_{CP} means light objects in front of a dark background, while a dark object on a bright background (e.g. print on newspaper) has a negative CP. Research shows that Contrast Polarity has an effect on object visibility, and this function quantifies this impact.

2.1.3. Exposure Time

The exposure time Δt describes the period of time the observer is able to see the symbol. Longer exposure times will significantly increase the probability of detection and discrimination. This term computes the effect of short exposure times on C_{th}. The term "*a*" is a function of symbol size α and the Adaptation Luminance L_a, which takes day and night adaptation into consideration.

2.1.4. Age

With increasing age, the opacity of the eye's lens grows, thus inducing stray-light in the eye [5]. This creates a diffuse spot on the retina instead of a sharp image. This veiling luminance is added to the background luminance (in equation 2), which decreases the symbol's contrast and creates glare. Function AF adds the influence of the age to equation 3. Figure 2 displays the influence of age on contrast sensitivity.

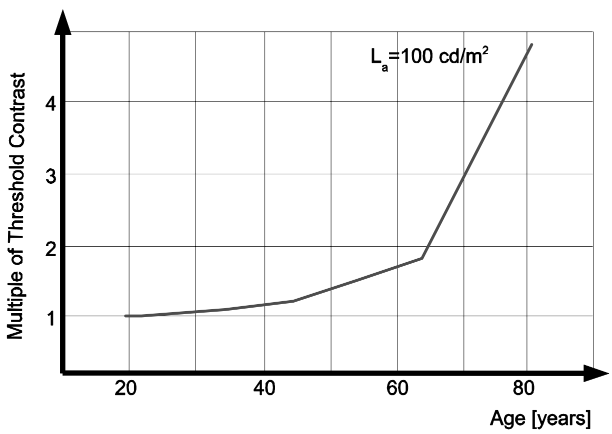

Figure 2: The influence of age on contrast sensitivity [4]

2.2. Luminance data input

In order to be able to conduct a visibility simulation, one will not only need the mathematical equations for the quantification of the human contrast perception, but also the necessary luminance data of the display to analyse.

Usually lighting simulations and renderings offer the user a 24-Bit bitmap representation of a three-dimensional scene. Sophisticated lighting simulation tools operate at a much higher dynamic range than the tone mapped 24-Bit output rendering, which makes it quite easy to obtain a high dynamic range image (HDRI) of the scene. This HDRI contains the result of the lighting simulation with negligible compression losses. In this work, RGBE HDRI was used as an interface between lighting simulation and perception prediction [20]. With the storage of luminance information for every pixel of an image it is possible to simulate the perceived brightness and contrast within a scene. The versatility of the HDRI interface also gives the option to not only use renderings but also HDRI photographs of real objects.

2.3. Adaptation Luminance computation

There are a lot of studies trying to define the Adaptation Luminance [6]. Unfortunately, most perceptual studies were conducted under laboratory conditions, which means that the test persons were exposed to a homogeneous luminance distribution in their field of vision. Under real life conditions this is a rather unlikely scenario that complicates the definition of the adaptive field size, which is the area in the field of view (FOV) contributing to the adaptation state. There is a great variety of different Adaptation Luminance definitions, ranging from 20° [7] over 6° [8] to 1° [9]. Furthermore, ergonomics handbooks state that the optimum FOV for desktop areas should not exceed 30° [10].

The Threshold Contrast simulation in this work will be based on a 30° adaptation cone. The base of this cone determines the adaptation by mathematical integration of each pixel's luminance value in that area. Nevertheless, the user is able to adjust the size of the area influencing the adaptation luminance.

2.4. Observer parameters

As soon as the HDRI is loaded, all necessary luminance data is available. Now, the user will have to enter a couple of observer-specific parameters before initiating the simulation:

- observer age,
- observer iris pigmentation colour (optional),
- time of exposure, and
- symbol size.

The eye colour (iris pigmentation) has an effect on the veiling luminance of glare sources. If an observer looks directly into a light source, the light rays will travel unobstructedly through the pupil, but if the observer is confronted with light in his peripheral field of view, the light will not travel through the pupil, but through the iris. In that case, the pigmentation of the iris will have an influence on the amount of light that will be absorbed in the iris. People with dark eyes will absorb more light in the iris, which leads to less stray light on the retina. Consequently, people with very light eye colours will suffer more from glare in their peripheral vision. This phenomenon can be computed with the CIE General Disability Glare Equation [21]. The equation's result is the veiling luminance which adds to the background luminance and thus decreases contrast.

2.5. Global and Local Contrast Threshold

If luminance data and observer parameters are present, the simulation will compute the Global Contrast Threshold $C_{thglobal}$ in the scene. This is the Contrast Threshold if the Adaptation Luminance equals the background luminance.

(4) $$L_a = L_{background}$$

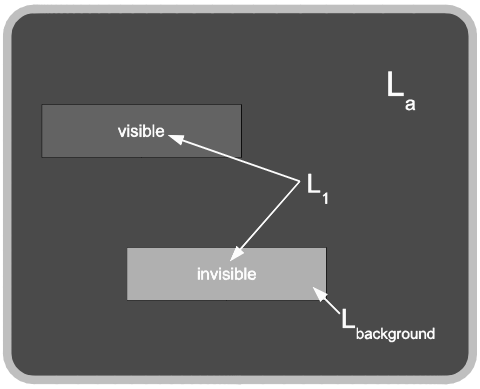

Figure 3: Local Contrast Threshold

Figure 3 shows a scenario, where the computation of the Global Contrast Threshold is insufficient. In this case, a symbol with the luminance L_1 may be visible upon the Adaptation Luminance L_a, but invisible upon the background luminance $L_{background}$. Here, it is necessary to compute a Local Contrast Threshold $C_{thlocal}$.

The following equation shows a method to compute the Local Contrast Threshold for heterogeneous backgrounds [11, 12, 13]:

(5) $$C_{thlocal} = \frac{1}{4} \cdot C_{thglobal} \cdot \frac{\left(1 + \frac{L_{background}}{L_a}\right)^2}{\frac{L_{background}}{L_a}}.$$

$C_{thlocal}=C_{th}(L_{background})$ → Local Threshold Contrast

$C_{thglobal}=C_{th}(L_a)$ → Global Threshold Contrast, using equ. 3

$L_{background}$ → Luminance of symbol background [cd/m²]

L_a → Adaptation Luminance [cd/m²]

Using equation 2 for the Local Contrast Threshold:

(6) $$C_{thlocal} = \frac{\Delta L_{thlocal}}{L_{background}}.$$

Inserting equation 6 into equation 5 and solving for $\Delta L_{thlocal}$ results in the final equation, which will be used in the visibility computation:

(7) $$\Delta L_{thlocal} = \frac{C_{thglobal} \cdot \left(L_{background} + L_a\right)^2}{4 \cdot L_a}.$$

$\Delta L_{thlocal}$ is the necessary difference between the Threshold Luminance $L_{thlocal}$ and its surrounding luminance $L_{background}$ to be perceptible. This means: If luminance values for L_a and $L_{background}$ are available, the software will compute the luminance difference, which is required to identify the visibility of the symbol on its corresponding background.

2.6. Supra-threshold contrasts

Equation 7 is used to compute the mandatory luminance for detecting symbols with a probability of 50%. Usually this is not the operating area of display layouts. In general, the predominant contrasts are much higher in order to ensure the readability of the display. This kind of contrast is called supra-threshold contrast.

If an assessment of the display content is requested, it will be necessary to develop a method to review supra-threshold stimuli.

2.6.1. PJND Method

Supra-threshold stimuli may be assessed using the PJND (*Perceptible Just Noticeable Difference*) Method by BAe Systems [14]. The PJND is an index for the visibility of supra-threshold contrasts. The higher the PJND index, the better the readability.

(8) $$PJND = \sqrt{LJND^2 + CJND^2}$$

Equation 8 denotes the composition of the PJND, which consists of the LJND (*Luminance Just Noticeable Difference*) and the CJND (*Chrominance Just Noticeable Difference*). The LJND is a measure for the luminance contrast, whereas the CJND describes the colour contrast. In fact, the LJND is very similar to the Threshold Contrast C_{th} described above. The interesting aspect of the PJND is its supra-threshold evaluation table. With this table, a display engineer is able to decide which multiple of this threshold is needed to depict the information on the screen with the necessary contrast.

Function	**PJND**
Attention getter	120
Warning and caution	90
Dynamic complex	70
Static complex	60
Status	50
Informative	40

Table 1: PJND index values

Table 1 shows various minimum PJND values for the design of display contents. This means that for instance a high risk warning information that shall draw the user's attention must have at least a PJND value of 120, which is 120 times the threshold stimulus. Now, the designer can differentiate between information with high and low priority and assign diverse PJND according to the information object's importance.

The PJND method has been developed with the help of pilots, using straightforward calculations. It is very easy to use and has been generated under real life conditions. Yet it has some minor disadvantages, which are:

- simple, non-photometric contrast,
- limited parameters (missing object size, exposure time, age, etc.),
- not suited for dark environments,
- and valid for positive contrast polarities only.

2.6.2. Visibility Level

The PJND method's disadvantages can be compensated by the use of a more differentiated Threshold Contrast basis. In this approach, the PJND index table is converted to the Threshold Contrast values above, creating multiples of C_{th}, or its corresponding luminance difference ΔL_{th} [15]:

(9) $$VL = \frac{\Delta L}{\Delta L_{th}}.$$

The Visibility Level (*VL*) is the ratio between the actual luminance difference ΔL and the Threshold Luminance ΔL_{th}. In other words: VL is the ratio between actual luminance and “necessary” luminance. A VL of 1 means a detection probability of 50%.

Now it is possible to convert the PJND index values to corresponding VL values. In order to create a unified scaling, the Visibility Level is noted as log VL (see Table 2).

Function	**PJND**	**log VL**
Attention getter	120	3.26
Warning and caution	90	2.57
Dynamic complex	70	2.28
Static complex	60	2.14
Status	50	2.00
Informative	40	1.84

Table 2: PJND and log Visibility Level

The index values of the *log VL* are used to categorise information into different priority classes. For a symbol to be an “Attention getter”, it must at least have a *log VL* of 3.26. The advantage compared to the classic PJND method is its wider scope of adjustable parameters. This means that the desired Visibility Level can be reached by more than mere contrast adjustment. The visibility improvement of symbol size and exposure time variation can now be quantified. It is also possible to estimate the difference of visibility due to observer age. One decisive improvement is the ability to quantify the effect of alternative layouts. It is commonly known that larger letters may be read better than small ones, but how much better remains the question. So how large do they have to be in order to reach a certain readability level?

These questions can now be answered by the new log VL index values. Engineers are now able to compare and evaluate different layouts and to make decisions in an early product development phase.

2.7. Experimental data

In order to validate the perception simulation model it was necessary to conduct a series of experiments with human subjects. Due to the use of many scientific publications for the development of the computational model it was possible to significantly reduce the number of required experiments.

Fourteen test persons aged between 23 and 36 participated in the validation experiment. The subjects were successively exposed to a sum of more than 4300 single contrasts, which were randomly generated by a computer and displayed under various Adaptation Luminances L_a. The automated experimentation software selected one of eight sans-serif letters and displayed it with a random foreground, background luminance and random size. After a randomised exposure time the subjects had to report the detected letter. This report was stored in a database. If the subjects did not detect any symbol, the simulation documented a zero-response. After a couple of seconds (also randomised) the computer chose a new letter and repeated the experimentation steps. In order to avoid fatigue, the duration time of one experiment was limited to a maximum of 15 minutes.

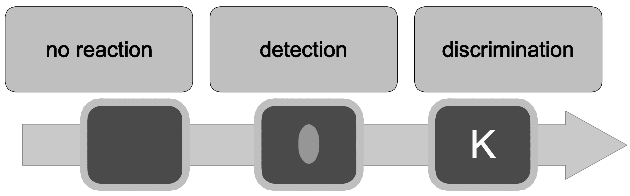

Figure 4: Perception levels

The subject's responses can be categorised into three perception levels (see Figure 4):

- **No reaction:** The test person did not show any reaction to the stimulus. Apparently, the symbol was invisible.
- **Detection:** The test person detected the symbol, but could not discriminate the correct letter.
- **Discrimination:** The test person reported the correct letter.

Since this study focuses on the simulation of the readability of displays, and especially on the reliability of this simulation, a *detection* is definitely insufficient for ensuring readability. Considering this classification, in 83.91% of the measured contrast detections, the simulation software predicted a correct result. In 15.81% the software made a minor error by stating an invisible contrast, when in reality the subjects were still able to discriminate the target correctly. Only in 0.27% of the experiments the simulation made a critical error by assessing a certain contrast condition as visible, although the test persons were not able to detect the target symbol.

Altogether, however, it was concluded that the mathematical models to predict Threshold Contrasts show good correlation with human perception.

3. VISUALISATION

The visualisation of the simulation results consists of two parts: The first part is a tone-mapped representation of the scene, while the second one is the direct Visibility Level output as an alphanumeric value. This division is required to distinguish between the visualisation of a scene's overall impression and the exact numerical assessment of the visibility.

3.1. Tone mapping operator

The tone mapping operator is a straightforward implementation of the computed Adaptation Luminance and the Contrast Threshold.

A sigmoidal curve is used to mimick the human perception of brightness [16]. The mathematical equation for such a function is:

(10) $$S(x) = S_{\max} \cdot \frac{x^n}{x^n + \sigma^n}.$$

σ is the value of x, where $S(\sigma) = 0.5\ S_{max}$. n is the gradient for the curve. This sigmoidal function compresses an unlimited input value x to a limited range between 0 and S_{max}.

Applied to the tone mapping process, equation 10 can be written as:

(11) $$R(x,y) = R_{\max} \cdot \frac{L(x,y)^n}{L(x,y)^n + \sigma^n}.$$

- **R(x,y):** Displayed brightness (grey scale) on the display for a real point (x,y) with luminance L(x,y).
- **R_{max}:** Maximum brightness (grey scale), which the monitor can produce (R_{max}=255).
- **L(x,y):** Luminance of a real point (x,y).
- **n:** constant, determining gradient (n=0.73).
- **σ:** real luminance (L_a) for: R=0.5 R_{max}.

- **x,y:** coordinates of real points in image plane.

Equation 11 compresses an unlimited range of luminance values to a confined range between 0 and R_{max}, which equals 255 for ordinary displays. When using HDR displays this value should be adjusted. The constant n describes the curve's gradient and is set to n=0.73 [17, 18, 23].

The sigmoidal shape of the curve creates a stronger compression of very light and very dark areas in the image. All luminances that are within two logarithmic units of σ (Adaptation Luminance) will be displayed according to the Weber-Fechner-Law. Luminances that have a lower or higher brightness will receive a compressed output, reproducing extremely high luminances as white and extremely low luminances as black, depending on the adaptation state of the observer (hatched areas in Figure 5).

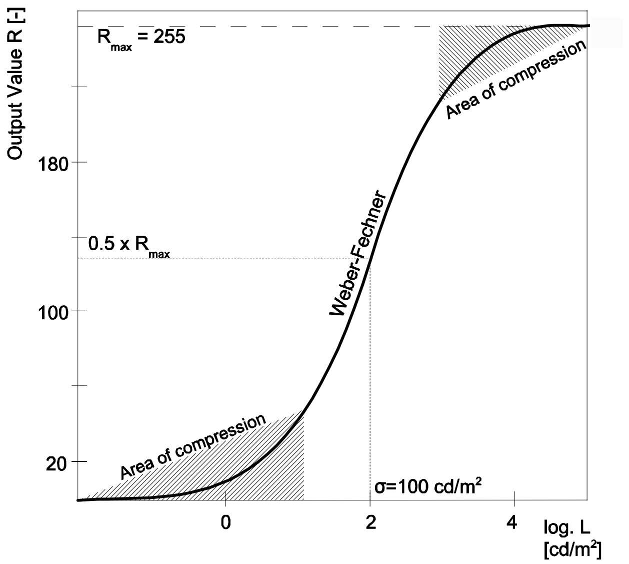

Figure 5: Straightforward Tone Mapping

In order to make better use of the available reproduction range, luminances that are perceived as black can be subtracted from the tone mapping process. This luminance level is called “black level” (L_B):

(12)
$$L_B = \left[B_2(\alpha) + B_3(\alpha) L_a^{\beta}\right]^{\frac{1}{\beta}}.$$

Equation 12 computes the black level L_B. B_i are functions of Adaptation Luminance L_a and symbol size α. The exponent β is set to 0.31 [19].

(13)
$$R(x,y)_{\mathrm{mod}} = \left\{\left[R_{\max} + R(L_B)\right] \cdot \frac{L(x,y)^n}{L(x,y)^n + \sigma^n}\right\} - R(L_B)$$

Equation 13 shows the modified Tone Mapping Operator for the exclusion of luminances that are equal to or lower than the black level.

3.2. Direct VL output

The correct visualisation of the Visibility Level is even more important than the illustration with an adequate tone mapping. For the analysis of the visual quality of a display content, the user relies on an explicit numerical scale. For the assessment of display visibility, tone mapping or false colour images are usually only appropriate for expert users. In this case, direct numerical output is required.

Figure 6 shows the implemented direct numerical output. The dotted curve marks the discrimination probability for a certain Visibility Level. The above-mentioned index values derived from the PJND method can be seen as vertical areas. The Visibility Level for a selected object is numerically displayed in the upper left corner of the image. In this case it is 2.98, which can also be seen as a rhombus in the according “Warning and Caution” area.

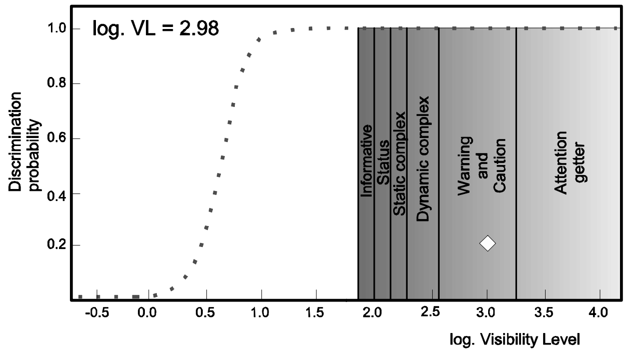

Figure 6: Visibility Level visualisation

4. INDUSTRIAL APPLICATION

The following application example is an air traffic control (ATC) display. This display is a new control unit that shall be running on a notebook-like application, offering the operator unprecedented flexibility in the selection of his working environment. This means that the user may operate this device under different conditions, for example in bright sunshine or in a dark room. Obviously, this must be considered while designing the layout of such a device.

Accordingly, two display variants were examined: one optimised for daylight use and one for a dark night-time environment. Irrespective of the variant, the following five process steps were applied:

- analysis of system ergonomics,
- bitmap to HDRI conversion,
- parameter transfer,
- measuring point assignment, and
- iterative modification process.

4.1. Analysis of system ergonomics

The first step is taken to analyse the system ergonomics. At this point the focus is on both user interface structure and logic. It is futile to optimise the visibility of certain objects, if these objects can be seen but not understood. This analysis shows that the original display layout has several disadvantageous human-machine-interface features. A first modification of the original layout improves the quality of the system ergonomics. These improvements consist mainly of resizing, renaming and re-allocating buttons and similar objects.

4.2. Image conversion

In the second step, this new layout has to be converted to a HDRI, thus creating a luminance image with the corresponding display characteristics. Due to the use of HDRI, it is possible to use various input sources such as lighting simulations and real world photographs.

4.3. Parameter transfer

The third step requires the manual input of the according parameters for the simulation: observer age and exposure times.

4.4. Measuring points

In the subsequent process step, several exemplary measuring points were selected and categorised. These points contain objects with low, medium and high priority targets, which shall be presented to the user with different urgency levels. Target Visibility Levels were appointed (nominal condition). Figure 7 shows the selected measuring points (marked with circles and red numbers).

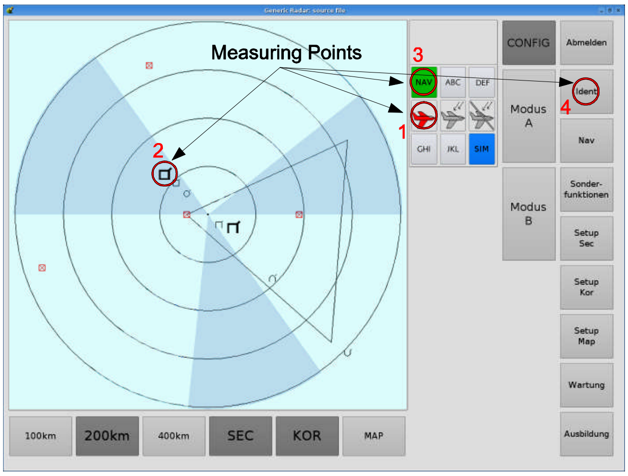

Figure 7: Air Traffic Control Display (measuring points)

1. **Alert**: This symbol marks the presence of aircraft in the airspace the operator is responsible for. This object shall have a very high Visibility Level. Target VL: 2.6.

2. **Radar contact**: These moving symbols display position and altitude of all aircraft in the vicinity. The desired Visibility Level is set to 2.3 because of the dynamic complexity of this symbol.

3. **Nav**: This reports the GPS status. Minor importance. Visibility Level: 1.8.

4. **Ident**: This button's label represents all buttons and labels in this layout. Visibility Level: 2.1.

It is the user's responsibility to assess the importance of the measuring points and to assign the required Visibility Levels. This assignment should be defined considering different aspects of the symbol characteristics, such as complexity, dynamics (moving or static symbol) and overall urgency.

4.5. Iterative modification

In the fifth and last step, the iterative modification process was initiated. During this process the actual configuration is simulated, assessed, reconfigured and re-simulated again, thus increasing the visibility of the entire system step by step. The reconfiguration contained mainly contrast and object size modifications. Figure 8 shows the major process steps.

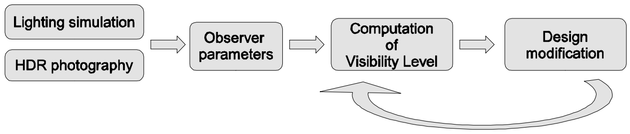

Figure 8: Simulation and modification process

4.6. Results

Table 3 illustrates the results of the iterative process. The first column depicts the number of the corresponding measuring point and the second column the required Visibility Level (nominal condition). The last four columns document the changes after each modification run.

Point	Nominal	Orig.	Mk 0	Mk 1	Mk 2
1	2.6	1.849	1.856	1.856	1.855
2	2.3	1.652	1.952	1.952	1.952
3	1.8	1.698	1.704	1.805	1.808
4	2.1	1.633	1.769	1.813	2.404

Table 3: ATC VL index values

It can be seen that not every symbol shows the desired readability. This is limited by the physical capabilities of the simulated TFT screen. Aircraft displays have a much higher contrast ratio which leads to higher VL. Although this can not be achieved by a conventional display the improvement of the visual quality can be estimated by looking at the resulting numbers.

It is important to notice the influence of changing luminances in the layout. Increasing or decreasing luminance or symbol size may have a remarkable influence on the overall Adaptation Luminance, leading to different Visibility Levels for all objects. This means that modifying object A, by either changing size or contrast, may affect the Adaptation Luminance for the complete layout, thus altering the Visibility Level of object B, without even changing any of object B's direct parameters.

The above mentioned night-time variant has a similar layout, but different luminance contrasts. In order to create a high degree of dark-adaptation, the overall brightness is set to a very low level. This is achieved by reducing background luminance and inverting the foreground colours. This generates a higher contrast compared to the day-time variant. Equation 2 shows that lower background luminances will induce higher contrasts, thus leading to higher Visibility Levels. During the iterative modification process of the night-time variant the VL increments were so high that the contrast of certain layout elements could be reduced again, in order to improve the differentiation to objects with higher priority. It is recommended to limit the achievable Visibility Levels to the according priority level. This means that the VL of a low-priority symbol should not exceed its corresponding VL area, so that information with higher urgency is not lost because of distracting low-priority input.

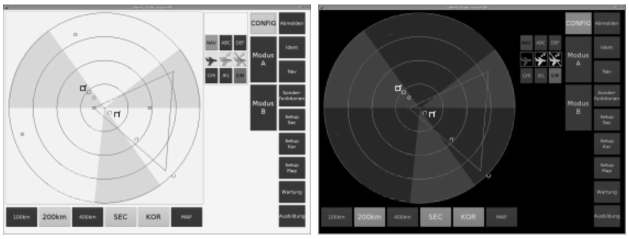

Figure 9: Day-time and night-time layouts

Figure 9 illustrates the conceptual differences between the day-time and night-time layout.

5. DISCUSSION

The following section will discuss certain aspects that are currently not incorporated in the perception simulation, but should be integrated in future versions.

5.1. Acuity and accommodation

Acuity of vision is the quality or sharpness of the image on the retina. The human eye is able to accommodate to different object distances. However, this accommodation process may take several seconds and constant repetition may lead to eye exhaustion and eventually to a degradation of vision quality by image blurring. Both the ability to accommodate and the required time depend to a great extent on observer age.

The simulation presented in this work does not compute acuity and accommodation, although these factors play a major role in the human vision process.

5.2. Centre of image as fixation point

In reality, the eye is never at rest. It constantly moves in short and unconscious saccades across the field of view. These movements can have angular speeds of several hundred degrees per second. However, the simulation assumes a constant point of fixation, namely the centre of the screen (unless the user changes that). This is also the centre for the adaptation cone.

5.3. Colour contrast

The Contrast Threshold simulation only computes luminance contrasts, colour contrasts are not considered. In aircraft cockpits, colour plays a minor role. For instance, the CJND contributes only about 10% to an overall PJND value in a standard cockpit. This means that in current aerospace technologies, colour contrasts are neglected. The increasing use of display capabilities will probably lead to the inclusion of colour contrast analysis. At the moment, the simulation provides the user with the corresponding CJND value in addition to the Visibility Level, so that the impact of colour contrasts may be estimated.

5.4. Transient adaptation process

The Contrast Threshold depends to a great extent on the Adaptation Luminance. If the illumination situation changes, the eye has to re-adapt to the new Adaptation Luminance. This process is called transient adaptation and during this time the Contrast Threshold is higher than in the steady state. A mathematical model for the calculation of this transient adaptation process is integrated in the simulation software, but has not been validated yet [22].

6. CONCLUSION

This study focused on the simulation of the human Contrast Threshold by compiling several psychophysical findings. Furthermore, a method was developed to evaluate supra-threshold contrasts with the PJND system, which expands the current system by a wider range of parameters. Display information readability can now be assessed by using this simulation. The designer can assign priorities to each object on the screen and later on modify the content accordingly.

This work shows that it is possible to simulate parts of the human perception for the development of a future product. Therefore, it is feasible to reduce the amount of experiments with test persons to the required minimum. This reduces not only the costs of experiments and expensive Mock-Ups, but also saves time and product revision steps.

In summary it can be ascertained that the new method described above facilitates the ergonomic design and review of virtual and existing products.

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