# M3art: A Database of Models of Canvas Paintings

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**Abstract.** M3art database contains data about colours behaviour in VIS and NIR spectral bands. The database is open, publicly available and should serve as the knowledge base for further study of optical properties of pigments, drawing materials and canvases. The content of database consists of FORS and digital camera data collected in range 400-1050nm. Measurements were made on up to three layer samples composed of canvas, underdrawing and colour layers. The colorants were selected to represent historical painting techniques in Gothic and Renaissance According to underdrawing acquisition ability four material categories were established.

**Keywords:** pigment database, FORS, underdrawing, penetration.

## 1 Introduction

The main issues for non-destructive and cost-effective evaluation of studied artwork are selection of an appropriate modality [1], of acquisition tools [2] and finally proper way of the measured data interpretation [3]. We focused on deep understanding of colour and behaviour of painting materials.

A few years ago we started with multimodal analysis of artworks (UV fluorescence, VIS - visible light spectrum and NIR - near infrared spectrum), thus we had to deal with the interpretation of measured data. In the literature [1] UV fluorescence is used for varnish repaintings and retouches (restoration intervention) detection and NIR for penetration of some pigment layers [4] of the artwork (especially for underdrawing visualization). Such optical effects were modelled for example in [5], [3], [6].

Description of layer based on reflected light only is insufficient in sense of its week conditioning. The unknown light absorption of top layers makes the interpretation of the measured data ambiguous. Observed high-value intensities may be caused by high reflectance of the top layer or high transmittance of the top layer combined with high reflectance of the bottom layer. These two effects cannot be distinguished without absorption/transmission measurement. Thus, our algorithms for automatic underdrawing detection has in such case many false positives in individual layer identification.

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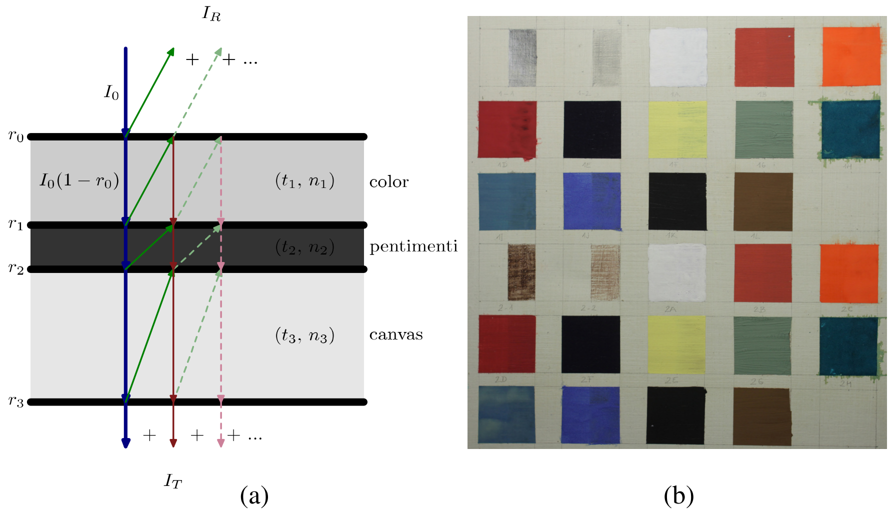



(a) (b)

**Fig. 1.** (a) Model of painted layers. For particular layer boundary coefficient r denotes the reflection, for the layer (n, t) describe layer index of reflection and transmission coefficient I denotes light intensity (subscripts R - reflected, 0 - emitted and T - transmitted). (b) The canvas (Mock-up no.1) with model samples imitating Gothic to Renaissance Italian painting. First two samples in the first and fourth row (samples no. 1, 2, 16, 17) are only with underdrawing (graphite and red clay, respectively). Pigments follow (lead white, cinnabar, red lead, madder, indigo, lead-tin yellow, green earth, verdigris, azurite, ultramarine, bone black and umber raw). Right half of each pigment sample contains underdrawing according to sample no. 1 and no. 16. Sample numbering runs from left to right and from top to down.

For elimination of these problems we have designed a study, similar to one described in [7], leading to better understanding of the behaviour of simple material layers in sense of their transmittance [8]. We have studied 13 different pigments and dyes and 10 different drawing materials. The colour pallets were selected to reflect specific historical painting techniques; only small constraints regarding the experiment setup were accepted.

We prepare 11 representative canvas models, each consisting of set of 30 square samples (see Figure 1 (b)). Each sample was multiple-times measured by spectrometer (FORS) and also by digital camera (VIS+NIR). In this way the sample reflection and transmission for both of its parts (with and without underdrawing) were measured. The measurements database is the major output of our study [9]. We have started the evaluation of the measured data and conclusions enabled to formulate recommendations with respect to the interpretability of the used painting materials.

## 2 Optical Representation

To be able to correctly interpret measured values we have to define appropriate physical model of the experiment setting (see Figure 1(a)). The painting is here understood as a set of certain number of colorant layers (similar to [10]).

We represent layer optical behaviour by parameters: $d$ - thickness, $a$ - absorption coefficient and $n$ - index of refraction. The vector ($d, a, n$) defines measured coefficients: $t$ - layer transmission and $r$ - reflection of the layer boundary (direct and scattered is included). The parameter $r$ is dependent on neighbouring layers

On each layer boundary we expect reflection according to Shlick's approximation [11] of Fresnel law:

$$r = \left(\frac{n_i - n_j}{n_i + n_j}\right)^2 \tag{1}$$

where the subscript $i$ assigns the parameter to the respective i-th layer. Note, that this equation is symmetric, $r$ is equal for a ray going from layer $i$ to layer $j$ as well as for a ray going from layer $j$ to layer $i$. Equation for $t$ we describe as:

$$t = e^{-\mathrm{ad}} \tag{2}$$

We have measured reflected and transmitted light intensities through different layer combinations (canvas, canvas-underdrawing, canvas-colour, canvas-underdrawing-colour). For each measurement we expect different thickness of the layers (samples are hand made) but constant absorption and index of refraction.

Measured values are:

$I_0$ – light intensity of the light source (equal to intensity falling on first layer)

$r_M$ – reflection coefficient of calibration target (Munsell Colour Checker - white)

$I_R$, $J_R$, $L_R$, $K_R$ – are light intensities reflected from canvas, canvas-underdrawing, canvas-colour and canvas-drawing-colour composites, respectively. These values are relative to the reflected light from calibration target ($I_0 * r_M$).

$I_T$, $J_T$, $L_T$, $K_T$ – are light intensities passing through canvas, canvas-underdrawing, canvas-colour and canvas-drawing-colour composites, respectively. $I_T$ is absolute value, $J_T$, $L_T$, $K_T$ are measured relatively to $I_T$.

We assume the constant energy equation:

$$I_0 = I_R + I_T + I_A, \tag{3}$$

where $I_A$ represents a light intensity absorbed in the artwork layers (mostly transformed to heat) and general energy loss. We reject from our model other energy transformations (i.e. creation or splitting of chemical bonds) during measurement. Similar energy equations are valid for all layer composites. As the index of refraction of the atmosphere was taken $n_0 = 1,00026$.

## 2.1 Limitations

Presented model assumes that all reflected and transmitted light was captured. Due to scattering (diffuse reflection) of light we are losing some intensity in spite of integration sphere usage. Basic correction is possible by a constant multiplication (according to an integration area) if the factor of scattering is constant across measurements.

In fact the scattering depends on the size of pigment particles and the roughness of surface. Second deficiency is wavelength shifting (fluorescence and luminescence), where we assume error less than 1% (shifting of light wavelength above 1050nm is included in absorption coefficient).

## 3 Full-Scale Model Samples (Mock-ups)

Respecting the period technology, 11 canvas full-scale models (mock-ups) have been prepared. On each of them, thirty 4 x 4 cm squares of different colours have been painted in regular matrix (see Figure 1(b)) using different pigments and binders and applied on grounds of various compositions. Each of these colour pallets corresponds to a specific historical painting technique, which, however, was modified having regard to specific conditions of the testing. Therefore, paints imitating Gothic panel painting technology were prepared on canvas support instead of wood to allow trans-luminiscence of the object from the backside. Further, instead of pure chalk (calcium carbonate), which is the most frequent material used in Gothic grounds north from the Alps in general, mixture of chalk with lead white (basic lead carbonate) has been applied imitating thus more likely Flemish and Netherlandish painting of the $16^{th}$ to $17^{th}$ century. These contextual "discrepancies" was guided by the effort to reduce the transparency of the white ground for infrared irradiation, which was necessary for the method calibration. In all squares, right half was under-painted by black and red brush drawing, respectively. Pigments used in paintings and drawings are listed in Tables 1 and 2.

Mock-ups number 1 to 4 imitate Gothic to Renaissance Italian painting, created on white ground prepared by mixing of 3 parts by volume of calcium sulphate (the so-called "Bologna chalk") (58100 Kremer Pigmente), 2 parts by volume of 7% aqueous solution of gelatine (Grac), 1 egg yolk and half-part by volume of polymerised linseed oil (3227 Umton). Similarly, mock-ups numbers 5-11 imitate Gothic to Renaissance painting of "north from the Alps" regions using calcium carbonate (chalk) instead of calcium sulphate (gypsum) in the ground. In our case, the original receipt was modified by addition of the lead white as follows: 2 parts by volume of calcium carbonate (chalk), (0100 Kittfort), 2 parts by volume of lead white, and 2 parts by volume of 7% aqueous solution of gelatine (Grac), 1 egg yolk and quarter-part by volume of polymerised linseed oil (3227 Umton).

For the underdrawing, following materials have been selected: graphite and red clay on the mock-ups 1 and 4, natural (vine or willow) and artificial charcoal on mock-up 2, iron Gall ink and sepia on the mock-ups 3 and 9, lead pencil and black chalk on the mock-up 5, graphite and galena (PbS) on the mock-up 6, red clay and lead pencil on the mock-up 7, natural vine black and black chalk on the mock-up 8, graphite, red clay, lead pencil, artificial charcoals, black chalk, vine black, sepia and iron Gall ink on the mock-up 10, and finally the silverpoint on the mock-up 11.

**Table 1.** List of names respective producers/codes, and abbreviations of used pigments and dyes for painting and materials for drawing. KP stands for Kremer Pigmente, ICC stands for the Institute of Inorganic Chemistry of the AS CR, v.v.i., KNH stands for Koh-I-Noor Hardtmuth.

PIGMENTS AND DYES FOR PAINTING

| | | |
|---|---|---|
| Verdigris | g.r. Lachner | VG |
| Lead white | 46000 KP | WL |
| Cinnabar | 10610 KP | CI |
| Red lead | Lachema Brno | RL |
| Lead-tin yellow | 10110 KP | LT |
| Green earth | 17410 KP | GE |
| Azurite | 10210 KP | AZ |
| Ultramarine | 10520 KP | UM |
| Umber raw | 40730 KP | UR |
| Bone black | 47100 KP | BB |
| Smalt | 10000 KP | SM |
| Madder | 37200-B KP | ML |
| Indigo | 36000-A KP | IG |

MATERIALS FOR DRAWING

| | | |
|---|---|---|
| Red clay (sinopia) | KNH | RC |
| Graphite | 12462 KP | GR |
| Natural willow charcoal | KNH | NC |
| Artificial charcoal | KNH | SC |
| Iron Gall ink | own production | IG |
| Sepia | 12401 KP | SP |
| Lead pencil | ICC | LP |
| Galena | 10900 KP | GA |
| Black chalk | 12450 KP | BC |
| Silverpoint | 11348 KP | AG |

**Table 2.** Summary of prepared samples. Left table contains pigments and dyes used for the sample painting; right table provides information about the material used for underdrawing in the respective sample. Each mock-up (one double-row) contains two sets of 15 positions on the canvas (columns), corresponding to samples with 2 different underdrawing materials (upper row, no.1-15, and bottom row, no. 16-30, respectively). Used abbreviations are listed in Table 1.

Pigments and dyes

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P01 | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | |
| | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | |
| P02 | | | WL | CI | RL | ML | IN | LT | GE | AZ | AZ | UM | BB | UR | |
| | | | WL | CI | RL | ML | IN | LT | GE | AZ | AZ | UM | BB | UR | |
| P03 | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | |
| | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | |
| P04 | | | WL | CI | RL | ML | IN | LT | GE | UM | AZ | UM | BB | UR | |
| | | | WL | CI | RL | ML | IN | LT | GE | UM | AZ | UM | BB | UR | |
| P05 | | | WL | CI | RL | ML | IN | LT | GE | IN | UM | AZ | BB | UR | SM |
| | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |
| P06 | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |
| | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |
| P07 | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |
| | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |
| P08 | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |
| | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |
| P09 | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |
| | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |
| P10 | SM | SM | SM | SM | SM | SM | SM | SM | SM | SM | SM | SM | SM | SM | SM |
| | SM | | | | | | | | | | | | | | |
| P11 | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |
| | | | WL | CI | RL | ML | IN | LT | GE | VG | UM | AZ | BB | UR | SM |

Drawing material

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P01 | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR | |
| | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC | |
| P02 | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | |
| | SC | SC | SC | SC | SC | SC | SC | SC | SC | SC | SC | SC | SC | SC | |
| P03 | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG | |
| | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP | |
| P04 | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | |
| | SC | SC | SC | SC | SC | SC | SC | SC | SC | SC | SC | SC | SC | SC | |
| P05 | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP |
| | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC |
| P06 | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR | GR |
| | GA | GA | GA | GA | GA | GA | GA | GA | GA | GA | GA | GA | GA | GA | GA |
| P07 | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC | RC |
| | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP | LP |
| P08 | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC | BC |
| P09 | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG | IG |
| | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP | SP |
| P10 | GR | GR | RC | RC | LP | LP | NC | NC | BC | BC | SP | SP | IG | IG | SC |
| | SC | | | | | | | | | | | | | | |
| P11 | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG |
| | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG | AG |

Pigments in chromatic layers represent traditional “Old-Masters” palette with lead white ($2PbCO_3{\cdot}Pb(OH)_2$), cinnabar (HgS), red lead – minium ($Pb_3O_4$), lead-tin yellow type I ($PbSnO_4$), green earth (iron-rich clay minerals), azurite ($2CuCO_3.Cu(OH)_2$), ultramarine ($Na_{8-10}Al_6Si_6O_{24}S_{2-4}$), raw umber (Mn-rich clay), verdigris (copper acetate), bone black (calcium phosphate), smalt (Co-containing glass) and organic dyes madder and indigo. Principally, animal glue and oil were used as binders on the muck-ups numbered 1, 2, 3, 5, 10, and 4, 7, 8, 9, respectively. On the mock-up 6 both glue and oil were used in the way “half and half”. On the mock-up 11 pure animal glue and emulsion containing glue and oil were combined. In cases lead white and indigo egg yolk was always added to the prevailing binder (either glue or oil) with the exception of mock-ups 6 and 7.

The surface of painting was left without any varnish, with the exception of mock-ups 6 and 11, where oil-resin varnish was applied to cover one half of each painted square. The composition of the varnish was as follows: 50g of dammar resin (60000 Kremer Pigmente), 7.5g of polymerised linseed oil (Stand Oil, 73201 Kremer Pigmente) and 150g of turpentine (70010 Kremer Pigmente).

## 4 Database of Measurements

Prepared samples were measured for their spectral transmission and reflection in range of visible light spectrum (VIS) and near infrared spectrum (NIR). Collected data are from 400nm up to 1050nm, each wavelength was measured separately.

### 4.1 Spectrometry

According to our optical model a layer is defined by (*n, a, d*) vector. In our samples the thickness of the layer *d* varies and therefore we have to take several independent measurements for each sample, more precisely for each sample half. For each sample half we took 4 measurements of reflection and two measurements of transmission (if it was possible[1]). In this way we obtained 8 reflection and 4 transmission measurements for the canvas (the left half of the samples 1 and 2 at each canvas) and for the canvas with drawing (the right half of those samples). The same was done for the colour on canvas (the left halves of the samples no. 3-15 and no. 18-30) and for the canvas-drawing-colour composite (the right halves).

**The equipment used for the spectral measurement:**

- Spectrometer USB 2000 [12] - Ocean Optics, range 428-1092nm
- Light source HL-2000-HP [13] - Ocean Optics, range 360-2400nm
- Optical fibres optimized for VIS, NIR
- 45° fibre holder for reflectance measurement and integrating sphere
- Collimating lenses for transmittance measurement
- X-Rite Munsell Colour Checker

Because of noise limitation useful range of spectrometer was from 440-1050nm.

[1] Transmission can be measured only on canvases 1-4 due to low power of light source.

### 4.2 Normalization

Spectrometer was calibrated by HL-2000-CAL light source. Reflectance of Munsell Colour Checker (CC) white $r_M$ was measured with HL-2000-CAL. The high power light source HL-2000-HP intensity $I_0$ was calibrated according to obtained $r_M$ (see Figure 2), to avoid oversaturation of spectrometer by direct light. Measured data $(I_R, J_R, L_R, K_R)$ were than measured relatively to $I_0 * r_M$, and this is the reason why reflectance can be higher than 100 % (see Figure 3). We select relation to the Munsell CC to achieve the repeatability of the measurement. The relative transmittance spectral data was normalized by the transmittance of the clear canvas. Thus we worked with the relative transmission measurements $(J_T, L_T, K_T)$ to $I_T$. Data was collected from circle area of 0,5cm in diameter. The spectrometer sensor takes 2048 values in the range 428-1092nm. The step in the wavelength is therefore approx. 0,324nm.

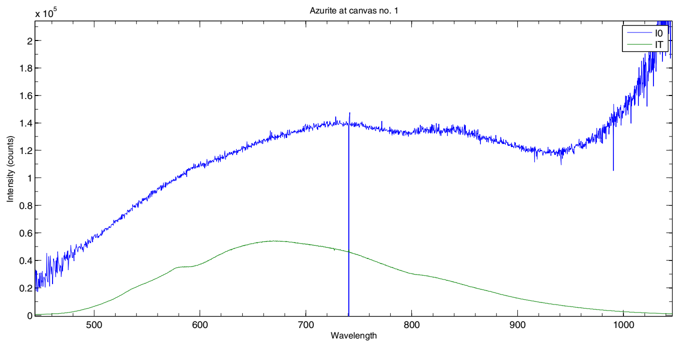



**Fig. 2.** Normalization of the spectrometer measurements. Blue (upper) curve denotes calibrated intensity of light source HL-2000-HP. Green (bottom) curve is average transmittance of canvas (canvas no. 1).

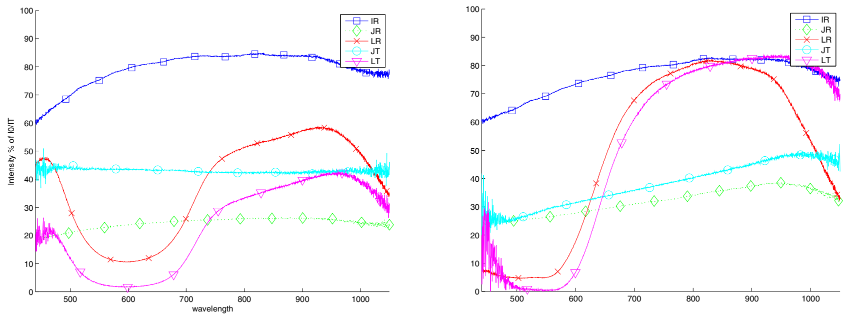
### 4.3 Camera Photometry

Prepared samples were also documented by digital camera. Our camera Cannon iRebel D500 was modified for NIR photography by removing of ICF. The spectral resolution of camera was enhanced with using filters and LED diodes.

**For camera photometry we used:**

- Canon iRebel D500
- Colour and IR filters – red, green, blue, yellow, orange, sepia and band pass filters 400-700nm, 680+, 720+, 760+, 850+ and 950+. Exact description can be found at [9].
- LED diodes with mean wavelength at – 398, 405, 466, 470, 506, 525, 565, 590, 605, 620, 660, 700, 880, 950nm. More detailed information can be found at [14].

The transmission of used filters and spectral characteristics of LED diodes can be found at [9], [15]. In spite of known characteristics data cannot be compared with the data from spectrometer. High temporal variance of emitted light intensity of LEDs or used light source affects interpretability of acquired values. These photos were used for evaluation of measured transparency of colours.




(a) (b)

**Fig. 3.** Measured transmittance and reflectance of azurite (a) on the canvas no. 1 and madder (b) on the canvas no. 5. IR denotes the reflectance of the canvas, LR and LT denote the reflectance and the transmittance of the canvas with azurite/madder layer, respectively and JR and JT denote the reflectance and the transmittance of the drawing on the canvas, respectively.

## 5 Results

The data from the proposed measurements in VIS and NIR spectral bands form the content of the m3art database of painting materials [9]. The m3art database should serve as the knowledge base for further study of optical properties of pigments, drawing materials and canvases.

For the underdrawing acquisition first conclusions were made. The Figure 3(a) shows results of measurement of ($L_R$, $L_T$) of azurite. The ratio of LR and LT curves determines ability for underdrawing detection by reflected or transmitted light. The higher reflectance ($L_R$) than transmittance ($L_T$) determines bad penetration ability of reflected light through azurite layer. Lower transmittance in general hardens penetration of layer also by transmitted light. Different behaviour of colour shows Figure 3(b), where ($L_R$, $L_T$) of madder were measured. Compared to azurite madder has lower ratio of reflectance/transmission. In other words, penetration of a madder layer is possible by the reflected light (in wavelengths above 700nm).

According to evaluation of the collected data we can split colour materials into four categories. First category contains materials whose transmission (LT curve, Figure 3) is almost zero and therefore they cannot be penetrated. In this category we put: bone black, verdigris and azurite.

Second category contains colours with high ratio of reflection/transmission. The reflected light cannot penetrate such (the reflection of top layer is in this case significantly higher than the reflection from bottom layer). For penetration of these colours and for the underdrawing discovery it is necessary to use a transmitted light. In this category we put lead white, lead-tin yellow and red lead.

Third category contains colours with high transmission in NIR compared to VIS spectral band. These colours can be penetrated by reflected and also by transmitted NIR light. In this category we put smalt, ultramarine, indigo, madder and cinnabar.

Finally, fourth category contains colours with similar behaviour in NIR as in VIS. Penetration of such colours is possible only in special cases (good condition of artwork, usage of contrast underdrawing, etc.). This category contains green earth and umber raw from our collection.

Note that fifth category should be defined: the colours possible to be penetrated by the reflected light only. But, such colour must have low reflection and high transmission, in other words such colour would be transparent. Materials belonging to fifth category are varnishes, which were not included in presented study.

## 6 Conclusion

We proposed and implemented m3art database - the open database with collected data about colours and their behaviour in VIS and NIR spectral bands. We made this data set public and available through Internet [9]. All our measurements are repeatable and comparable because of the calibration.

We suggested base methods how to penetrate 8 colours from the representative Gothic/Renaissance set for underdrawing detection and identified the remaining 5 colours as the ones for which the penetration ability of NIR is poor or none. We define 4 categories of colours according to the possibility of their penetration in NIR spectrum. We conclude that transmission measurement is more universal than (more common) reflection measurement for underdrawing detection and should be used when possible (i.e. canvas paintings, sufficient light transmission).

Our following research will focus on the computation of optical properties of samples (*n, a, d*) and their stability in practice. We expect significant influence of different layer thickness, concentrations of binding media/pigment and age of the layer. We also focus on preparation of new mock-ups and their measurement, which enrich the m3art database.

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