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THE INFLUENCE OF THE THICKNESS OF THE GRID IN MUNKER-WHITE EFFECT

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Original scientific paper
This paper shows the influence of the thickness of the grid on the intensity and assimilation in Munker-White effect. It can be described as the effect of assimilation of grey rectangular elements into the colour of unbroken lines. They are perceived darker in combination with grey and black lines, and lighter in white and grey combination. Measured colorimetric differences are shown in CIEDE2000 system. Three polynomial statistical regression models were created based on the results. Models contain polynomial expressions describing the influence of the grid thickness on the intensity shift of rectangular objects in Munker-White effect. Models were tested statistically and the analysis of measured parameters shows their statistical representativeness.

Keywords: *assimilation; mathematical model; Munker-White; regression analysis; simultaneous contrast*

Utjecaj debljine rešetke kod Munker-Whiteovog efekta

Izvorni znanstveni članak
U radu je opisan utjecaj debljine rešetke na intenzitet simultanog kontrasta i asimilacije kod Munker-Whiteove efekta. Isti možemo opisati kao pojavu gdje se sivi elementi (pravokutni elementi) asimiliraju s bojom neprekinutih linija, koje se u kombinaciji sa sivo-crnim linijama percipiraju tamnije, a sa sivo-bijelim linijama svjetlije. Dobivene kolorimetrijske razlike prikazane su u CIEDE2000 sustavu. Na temelju rezultata napravljena su tri polinomijalna statistička regresijska modela. Modeli sadrže polinomijalne izraze koji opisuju utjecaj debljine rešetke na intenzitet pomaka pojavnosti svjetline pravokutnih elemenata kod Munker-Whiteovog efekta. Modeli su statistički testirani te je analizom dobivenih parametara pokazano da su statistički reprezentativni.

Ključne riječi: *asimilacija; matematički model; Munker-White; regresijska analiza; simultani kontrast*

1 Introduction

While attempting to analyse the psychophysical visual effect shown in the design of Susan Hirth [1] Michael White designed in 1979 a brand new black and white grid structure known as Munker-White illusion [2]. Today it is known as the strongest illusion of whiteness [4] and it connects psychophysical effect of simultaneous contrast and assimilation. Simultaneous contrast is the psychophysical effect which causes the shift of colour appearance in response to the colour change of the background. Munker-White illusion contains grey rectangular elements that are assimilated into the parallel coloured lines [2, 3, 4]. Fig. 1 shows the change between grey elements and black and white lines. Grey rectangular elements appear darker in combination with grey and black lines. They appear lighter in combination with grey and white lines.

This effect has been and is the object of numerous scientific researches. Research of Munker-White and other psychophysical effects is often interdisciplinary and involves different research scientific areas such as graphic technology, psychology, medicine, neurology and math.

Figure 1 Munker - White effect

The structure of Munker-White effect contains the composition of parallel lines with rectangular elements placed in between (Fig. 1, left) and within (Fig. 1, right). The structure is universal and is often found in graphic arts and different types of design [5]. The influence of Munker-White effect on graphic reproductions is intensively studied [6, 7]. Gained results allow more efficient control of colour information and better use of Munker-White effect in graphic design.
A series of mathematical models were developed in order to describe the appearance of psychophysical visual effects including the Munker-White effect.

Most of the models come from the so-called DOG rule (*Difference of Gaussian*) [8]. DOG is a mathematical algorithm based on Gauss filters. Gauss filters do not allow areas of high contrast. Some new mathematical models explain the shift of lightness perception with neural filters for processing spatial frequency information and orientation of contrast. Munker-White effect is best described by filters sensitive to contrast direction according to so-called ODOG rule (*Oriented Difference of Gaussian*) [9, 10].

Lately, there have been attempts to define unique mathematical theory for description of different psychophysical effects including Munker-White effects. It was determined that a measurement scale of two dimensional interval differences of Gauss filter [11] can be made. It represents the mathematical model for common description of chromatic simultaneous contrast and assimilation for description of Munker-White effect.

The purpose of this paper is to describe and research the scale of influence on perception by Munker-White effect in order to add to the unique mathematical theory for description of psychophysical effects.

The application of gained results will enable more efficient usage of this psychophysical effect in different media, therefore enhancing the quality of graphic product.

2 Experimental part

2.1 Research description

Experimental part is composed of instrumental and visual research.

Spectrophotometric measurement and display of CIE $L^*a^*b^*$ values are made in instrumental part of the experiment. Relevant fields were defined with the visual part of the experiment. The method of binocular adjustments was used [12].

Deviations in perception caused by certain manifestation of visual effect are shown as difference of lightness ΔL_{00} by applying reference sample from colour atlas to the sample [7, 14].

Difference in colour ΔE_{00} and lightness ΔL_{00} is calculated with formula [13]:

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H'_{ab}}{k_H S_H}\right)^2 + + R_T \left(\frac{\Delta C'_{ab}}{k_C S_C}\right)\left(\frac{\Delta H'_{ab}}{k_H S_H}\right)\right]^{-0,5}, \tag{1}$$

$$S_L = 1 + \frac{0{,}015\left(\overline{L} - 50\right)^2}{\left[20 + \left(\overline{L} - 50\right)^2\right]^{0,5}}, \tag{2}$$

$$S_C = 1 + 0{,}045\overline{C}'_{ab}, \tag{3}$$

$$S_H = 1 + 0{,}015\overline{C}'_{ab}\,T, \tag{4}$$

Where

$$T = 1 - 0{,}17\cos(\overline{h}'_{ab} - 30°) + 0{,}24\cos(2\overline{h}'_{ab}) + + 0{,}32\cos(3\overline{h}'_{ab} + 6°) - 0{,}20\cos(4\overline{h}'_{ab} - 63°), \tag{5}$$

$$R_{\mathrm{T}} = -\sin(2\Delta\Theta)R_C, \tag{6}$$

where

$$\Delta\Theta = 30\exp\left\{-\left(\frac{\overline{h}'_{ab} - 275°}{25}\right)^2\right\}, \tag{7}$$

$$R_C = 2\left(\frac{\overline{C}'^{7}_{ab}}{\overline{C}'^{7}_{ab} + 25^7}\right)^{0,5}. \tag{8}$$

2.2 Design and reproduction of test samples

11 variants of achromatic Munker-White samples with different grid thickness were made (Fig. 2, Tab. 1) for the experiment. All the samples are rectangular elements with the same parameters L = 75,03; a^* = 2,63; b^* = −6,88. Values x, y and h are modified for the experiment.

Dimensions of sample fields were defined in accordance with standard observing conditions (ISO 3664:2009 which defines observation conditions for printing industry and professional photography). The height of test field, viewing angle and test subject distance were calculated from formula [15]:

$$\tan\left(\frac{\theta}{2}\right) = \frac{H}{2}, \tag{9}$$

$$\theta = 2\arctan\left(\frac{h}{2d}\right), \tag{10}$$

where θ is the viewing angle, H is the test sample size.

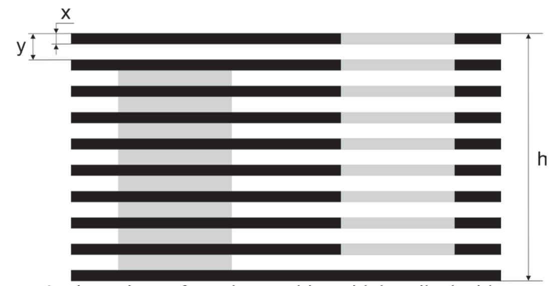

Figure 2 Dimensions of Munker - White grid described with x, y and h

Table 1 Dimensions of different variants of Munker-White grid in mm and grid coverage percentage

Nr. of samples	Grid dimensions			Percentage of coverage (x/y) / %
	x	y	h	
1	1	12	106	8,33
2	2	11,5	106,5	17,39
3	3	11,5	107,5	26,09
4	4	12	108,5	33,33
5	5	11,5	109	43,49
6	6	12	110	50,00
7	7	12	111	58,33
8	8	12	111	66,67
9	8,5	11	111	77,27
10	9	11	111	81,82
11	10	11	111	90,91

Test sheet was made in Adobe Photoshop CS5 using Lab colour space (Fig. 3). It contains test samples and the appropriate colour atlas.

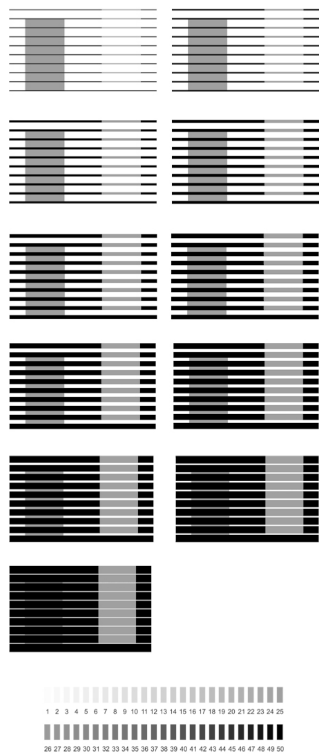

Figure 3 Test sheet (test samples and atlas)

Reference atlas was made for evaluation of test samples. Atlas is based on the alteration of perception attributes within *Lab* colour model. It contains complete potential area of perception. Specific fields of atlas have appropriate CIE $L^*a^*b^*$ values of spectrophotometric measurements.

Test samples were printed on calibrated printing machine Canon iX6550. Files were rendered using Adobe Photoshop CS5. Rendering from Lab colour space to Canon iX6500 series MP colour profile was done using perception rendering and Adobe ACE colour engine. Canon matte photo paper, weight 170 g/m^2 was used as printing substrate. Prior to printing substrate was conditioned in the room for 48 hours according to prescribed standard environmental conditions (temperature of 23 °C and 55 % relative humidity). Test runs were made at qty. of 10 samples.

2.3 Instrumental analysis

X-Rite SpectroEye was used for measuring samples and reference fields. It measures wavelengths from 380 to 730 nm in increments of 10 (with inner resolution of 3,3 nm). Light source is gaseous wolfram type A. Lighting geometry is 45°/0°, DIN 5033 with linearisation of ±0,01D.

Each control field in run of 10 copies was measured 5 times after which statistical values were taken in order to enhance statistical accuracy.

2.4 Visual analysis

38 people of mixed population of average age of 20 were used for the visual part of the research. Everyone passed the Ishihara test prior to testing. Visual evaluation was performed in controlled ambient conditions (ISO 3664:2009: 10° viewing angle, distance from sample to test subject 60 cm, natural matte grey surroundings, artificial lights). Test samples were evaluated under standard CIR D75 (7500K) lighting.

Visual evaluation was made in accordance with the method of binocular harmonisation. Test sample and reference file were in the field of view at the same time. Every person had to choose a field in the atlas most like the surface covered by rectangular elements between black lines (left) and within black lines (right) of the test sample (Fig. 4).

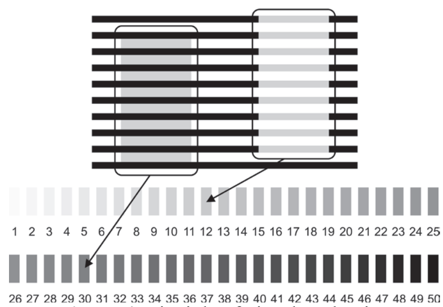

Figure 4 Principle of visual evaluation

Table 2 Mean value, median and standard deviation of L^*, a^* and b^* components of analysed elements (left)

Percentage of coverage (*x*/*y*) %	*L**			*a**			*b**		
	Mean value	Median	Std. deviation	Mean value	Median	Std. deviation	Mean value	Median	Std. deviation
8,33	70,66	70,96	3,37	2,46	2,51	0,32	−7,82	-7,83	0,34
17,39	69,13	69,35	4,41	2,32	2,50	0,39	−7,72	−7,83	0,42
26,09	66,77	66,05	4,35	2,11	2,01	0,42	−7,56	−7,42	0,45
33,33	67,11	66,05	5,47	2,07	1,89	0,45	−7,46	−7,37	0,36
43,49	65,26	66,05	6,11	1,98	1,90	0,45	−7,43	−7,32	0,49
50,00	63,99	64,16	7,10	1,90	1,90	0,50	−7,31	−7,32	0,48
58,33	63,26	64,14	7,95	1,89	1,90	0,59	−7,27	−7,20	0,61
66,67	64,82	67,72	8,64	1,97	2,01	0,59	−7,37	−7,41	0,59
77,27	67,00	69,35	6,70	2,16	2,50	0,53	−7,15	−7,53	2,39
81,82	70,57	72,56	6,63	2,41	2,50	0,53	−7,64	−7,81	0,36
90,91	75,18	72,56	6,59	2,78	2,77	0,42	−7,80	−7,83	0,36

Table 3 Mean value, median and standard deviation of L^*, a^* and b^* components of analysed elements (right)

Percentage of coverage (*x*/*y*) %	*L**			*a**			*b**		
	Mean value	Median	Std. deviation	Mean value	Median	Std. deviation	Mean value	Median	Std. deviation
8,33	81,84	81,89	5,35	3,21	3,29	0,26	−7,85	−7,84	0,36
17,39	80,11	80,83	4,30	3,14	3,22	0,27	−7,33	−7,81	2,47
26,09	80,04	79,74	4,31	3,13	3,22	0,27	−7,77	−7,84	0,25
33,33	80,36	79,74	4,47	3,14	3,22	0,27	−7,80	−7,84	0,27
43,49	79,54	79,74	4,13	3,10	3,22	0,27	−7,73	−7,82	0,23
50,00	79,17	79,74	4,04	3,12	3,22	0,24	−7,77	−7,84	0,26
58,33	79,16	80,83	3,91	3,12	3,22	0,25	−7,79	−7,84	0,22
66,67	78,58	78,54	4,35	3,05	3,09	0,22	−7,71	−7,79	0,26
77,27	78,23	78,54	4,27	3,03	3,09	0,23	−7,67	−7,52	0,25
81,82	78,64	78,54	4,93	3,00	3,09	0,32	−7,73	−7,79	0,28
90,91	78,12	77,98	5,07	2,98	3,05	0,32	−7,75	−7,82	0,25

3 Results and discussion

Results were statistically analysed with computer software Statistica 12. Descriptive statistic, correlation and polynomial regression analysis of the samples were made.

3.1 Descriptive sample statistic

Tabs. 2 and 3 show descriptive statistical analysis of psychophysical visual experiment, mean values, medians and standard deviations of perceived L^*, a^*, b^* values of analysed elements (Fig. 4, Tab. 1).

Values were calculated with statistical analysis of results of visual experiment on 38 people.

3.2 Regression analysis of samples

Based on gained results (Tab. 2 and 3) CIEDL00 values were calculated in perceived lightness on rectangular elements of the grid (Tab. 4) for appropriate coverage percentage. Colorimetric deviations between percepted and physical lightness of analysed elements were calculated (Tab. 4).

Differences were calculated for certain coverage percentage marked as *P*.

Table 4 CIEDL00 Colorimetric differences of analysed elements

Percentage of coverage P / %	Value ΔL^*_{2000} (between grid, left)	Value ΔL^*_{2000} (within grid, right)	Value ΔL^*_{2000} (between)
8,33	−3,27	4,79	8,05
17,39	−4,45	3,61	8,05
26,09	−6,32	3,56	9,87
33,33	−6,05	3,77	9,81
43,49	−7,54	3,21	10,74
50,00	−8,59	2,95	11,53
58,33	−9,2	2,95	12,13
66,67	−7,90	2,54	10,43
77,27	−6,14	2,3	8,43
81,82	−3,34	2,58	5,92
90,91	0,06	2,22	2,11

Polynomial regression analysis was used to process available data from Tab. 4. Results are shown in Tabs. 6, 7 and 8.

Correlation analysis of variables ΔL^*_{2000} (between grid), value ΔL^*_{2000} (within grid) and value ΔL^*_{2000} (between) gave Pearsons correlation coefficients (Tab. 5).

Table 5. Results of correlative analysis of variables ΔL^*_{2000} (between grid), ΔL^*_{2000} (within grid) i value ΔL^*_{2000} (between) with level of significance $p < 0,05$. Table contains the appropriate p-values

Variables	ΔL^*_{2000} (between grid, left)	ΔL^*_{2000} (within grid, right)	ΔL^*_{2000} (between)
ΔL^*_{2000} (between grid, left)	1,00 *p*=.....	0,0129 *p*=0,970	0,9634 *p*=0,000
ΔL^*_{2000} (within grid, right)	0,0129 *p*=0,970	1,00 *p*=.....	0,2564 *p*=0,447
ΔL^*_{2000} (between)	0,9634 *p*=0,000	0,2564 *p*=0,447	1,00 *p*=.....

Results in Tab. 5 show high negative correlation of variables ΔL^*_{2000} (between grid) and ΔL^*_{2000} (between) with Pearson's correlation coefficients $r = -0,9634$. This correlation is statistically significant with level of significance $p = 0,000 < 0,05$. Correlations between other variables are not statistically significant.

3.3 Regression model of colorimetric deviation in lightness between Munker-White grid

Square regression model gives the dependance of intensity of lightness shift in regard to the thickness of the grid for the rectangular elements that are within the system of parallel lines. Square regression model was chosen based on the parameters which show high degree of similarity with the visual research data.

Table 6 Result of regressive analysis of variable ΔL^*_{2000} for rectangular elements between parallel lines (left) in dependance on coverage percentage of Munker-White grid

N=11	Results of Regression Analysis for Dependent Variable: ΔL^*_{2000}, *R*= 0,93626682, R^2=0 ,87659555, Adjusted R^2= 0,84574444, *F*(2,8)=28,414, *p*<0,00023, Standard Error of Estimate: 1,0809					
	b^*	Std. Err. of b^*	b	Std. Err. of b	$t(8)$	p-value
Free coefficient			0,7703	1,213180	0,63492	0,543209
p	−3,83773	0,553363	−38,6503	5,572998	−6,93528	0,000120
p^2	4,10677	0,553363	40,4074	5,444659	7,42147	0,000075

Determination coefficient R^2 = 0,87659555 is very close to maximal value 1 which shows that the model is representative. This model can interpret 87,66% of square errors. Significance of regression is determined with p-value which for this model is p = 0,00023 < 0,01. Corrected determination coefficient adjusted R^2= 0,84574444 is another indicator of high quality of the model. The parameter depends on number of liberty degrees of freedom. Standard error SE = 0,10809 gives an average deviation of data from regression curve. SE and p-values of P and P^2 are relatively small which shows the value of the model. P-values are below significance level of 0,001.

Regression polynomial of second order which gives the analytical description of dependance of lightness shift ΔL^*_{2000} in dependance on percentage of grid coverage percentage P was calculated.

$$\Delta L(P) = 0,7703 - 38,6503P + 40,4074P^2.$$

Results show the direction and intensity in lightness shift (Fig. 5). In almost all cases visual square elements are perceived as lighter than their measured values. Largest colorimetric value of −8,4721 is found in grid coverage of 47,82 %:

$$\min\{0,7703 - 38,6503x + 40,4074x^2\} \approx$$
$$\approx -8,4721 \text{ at } x \approx 0,478258.$$

Colorimetric differences are smaller with very small and very large coverage percentage.

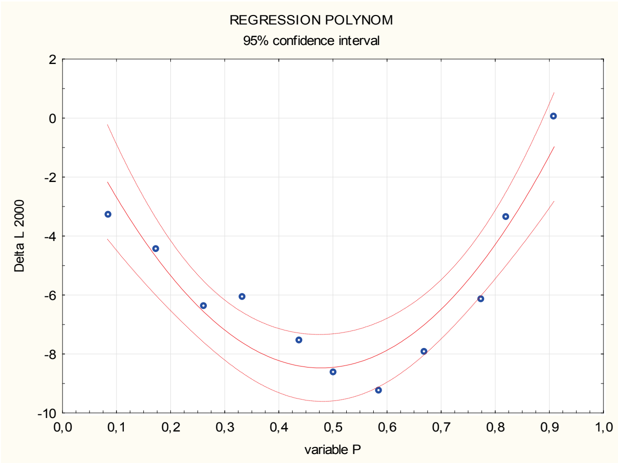

Figure 5 Graphical representation of regression polynome

3.4 Regression model of colorimetric differences in ellement within Munker- White grid

Combination of multiple polynome regression models determined that the data fit best in linear regression model. It can be determined with high statistical precision that the difference of colorimetric values dependant on thickness of the grid is linear.

Determination coefficient of regression model is R^2 = 0,87514183 while the corrected coefficient of determination is adjusted R^2 = 0,86126870. This points to high statistical quality of the model. Standard error is very small at SE = 0,28413 and p-value is $p = 0,00002 < 0,001$. All p-values (empirical or noticed significance values) of variables are insignificant.

Linear regression polynomial gives analytical expression for calculation ΔL^*_{2000} compared to grid coverage percentage P for rectangular elements within lines:

$$\Delta L(P) = 4,44887 - 2,61141P.$$

Table 7 Result of regression analysis of variable ΔL^*_{2000} for rectangular elements within parallel lines (right) in dependance on coverage percentage of Munker-White grid

N=11	Results of Regression Analysis for Dependent Variable: ΔL^*_{2000}, R= 0,93549015, R^2= 0,87514183 Adjusted R^2= 0,86126870, F(1,9)=63,082 p<0,00002, Standard Error of Estimate: 0,28413					
	b^*	Std. Err. of b^*	b	Std. Err. of b	t(9)	p-value
Free coefficient			4,44887	0,186341	23,87481	0,000000
p	−0,935490	0,117784	−2,61141	0,328793	−7,94240	0,000023

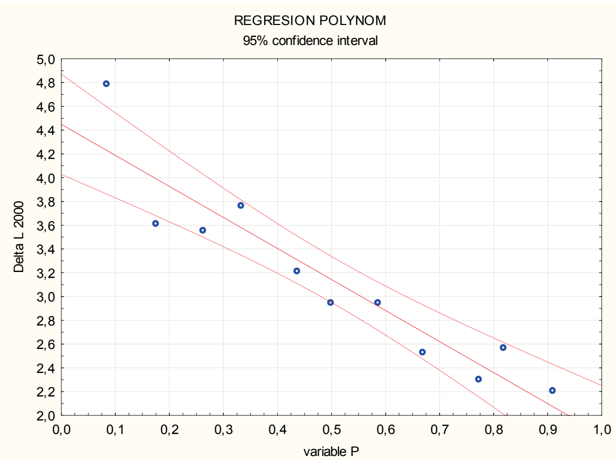

Figure 6 Linear regression polynome

Visual square elements within lines are percepted as lighter than their physical values. Colorimetric differences reduce with the increase in grid coverage. The enlargement of grid coverage percentage by 1 % will cause the reduction of colorimetric difference by 0,025 (Fig. 6).

3.5 Regression model of colorimetric differences between different elements of the grid

Polynomial regression analysis of colorimetric differences in perception of rectangular elements between lines and elements within lines was conducted. It was shown that square regression model best describes the observed phenomenon. Results of regression analysis are shown in Tab. 8.

Statistical quality of gained model is very high considering the gained parameters. Determination coefficient is R^2 = 0,87814673, corrected determination coefficient is adjusted R^2 = 0,84768342. Standard error is SE = 1,1137 while p-value of the model is $p = 0,00022 < 0,001$. All p-values are neglectable.

Table 8 Result of regression analysis of variable ΔL^*_{2000} for rectangular elements between and within parallel lines (in between) in dependance on coverage percentage of Munker-White grid

N=11	Results of Regression Analysis for Dependent Variable: ΔL^*_{2000}, R= 0,93709484 R^2= 0,87814673 Adjusted R^2= 0,84768342, F(2,8)=28,826 p<0,00022, Standard Error of Estimate: 1,1137					
	b^*	Std. Err. of b^*	b	Std. Err. of b	t(8)	p-value
Free coefficient			4,0561	1,249995	3,24487	0,011791
P	3,24770	0,549874	33,9145	5,742119	5,90626	0,000359
p^2	−3,75374	0,549874	−38,2962	5,609886	−6,82655	0,000134

Polynomial regression gives the function which enables prediction of the manifestation intensity of Munker-White effect in dependance on the grid thickness.

$$\Delta L(P) = 4,0561 + 33,9145P - 38,2962P^2.$$

The analysis of gained curve determined it gains maximal values of Munker-White effect for coverage percentage of 44,28 % (Fig. 7). In that case the shift in witness is $\Delta L^*_{2000} = 11,5646$:

$$\max\{4,9561 - 38,9145x + 38,2962x^2\} \approx$$
$$\approx 11,5646 \text{ at } x \approx 0,442792.$$

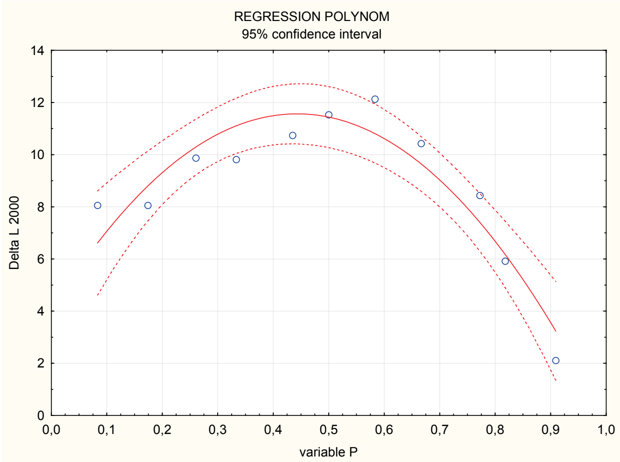

Figure 7 Manifestation of regression polynome of Munker-White effect in dependance on the thickness of the grid

4 Conclusion

Results clearly show the influence of the thickness of the grid on the intensity of simultaneous contrast and assimilation in Minker-White illusion. Polynomes for the calculation of colorimetric differences between percepted and physical lightness on visual elements between parallel lines, within them and between them were determined.

Values for which the thickness of the grid in which the values of simultaneous contrast and assimilation are maximal were determined. Gained expressions enable efficient calculation of intensity of simultaneous contrast and assimilation on graphic reproduction containing Munker-White grid.

The application of results enables upgrading of current models connected with psychophysical effects and more efficient usage of this effect in different media, in graphic design of products.

It is necessary to apply this methodology to different psychophysical effects. The same results will enable greater possibility of application of psychophysical effects in modern graphic design.

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