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Visual acuity in polychromatic light

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The resolution limit is one of the most important measures used in evaluating the human vision quality. It is measured typically by presenting a test object in the form of periodic fringes of different spacing to the observer subjected to the test and determining the highest spatial frequency still correctly resolved. In this paper we describe the results of such experiments for different colours of illuminating light. Our measurements suggest that the resolution in blue light is substantially worse than in white light. Using laser light it is easy to generate the sinusoidal pattern of high contrast. The resolution measurement with such object is almost 20% worse than in incoherent light of the same colour.

1. Introduction

For the evaluation of the human vision quality such measure of the visual acuity as the resolution limit is most frequently used [1], [2]. The two point resolution limit is defined as the smallest distance (linear or angular) between two point sources seen separately. Since in practice the observed objects or scenes are only exceptionally composed of separate points but more often contain linear and extended patches, the other definition may be suitable. It is based on the observation of periodic test objects such as Ronchi ruling (set of parallel, equidistant straight lines) or sinusoidal grating [3], [4]. The (linear) resolution refers to such grating which is barely resolved by the observer. If the spacing of stripes is even slightly smaller, the observer cannot resolve the structure of the test but sees it as a uniform, grey field. The resolution limit may be expressed in terms of distance (usually angular) between such lines and denoted MAR (minimum angle resolution, measured in arc min), or in terms of spatial frequency of the test structure and denoted ω (measured usually in $\deg^{-1}$). In optometry the logarithmic scale is typically used (logMAR) [5].

Visual acuity depends on many factors of different nature. Some of them are connected with the optical quality of an eye, the others are consequences of the structure and functioning of the retina. The whole visual pathway, including optic nerves and brain is influencing visual quality as well. While considering the retinal image, two main reasons of the limited resolution can be identified: diffraction on the pupil and aberrations. The grain structure of the retina and spatial and spectral distribution of its sensitivity limit the resolution of the detected image as well.

Therefore, the visual acuity is often measured in order to evaluate the quality of vision and to detect such refraction errors as myopia, hypermetropia, astigmatism, accommodation insufficiency or failures in colour vision [6], [7].

So far, the measurement of the visual acuity has been done in incoherent light. The problem of changes in the visual acuity in coherent light has been somehow neglected. However, this problem seems to be very interesting.

In this paper we describe the preliminary results of visual acuity measurements in dependence on the spectral content of light illuminating the observed test and the degree of coherence. The measurement has been done both in coherent and in incoherent light, which allowed to make the first general comparison. Two methods were applied to measure the visual acuity. In the first method, a set of Ronchi patterns with different spatial frequencies was used. The patterns were printed on paper. In the second method sinusoidal interference fringes served as the pattern.

2. First method

In this section we describe the first method used for the visual resolution measurements. We performed such measurements under different illumination conditions: in white light, in polychromatic light, in monochromatic incoherent light and in laser light. We used a subjective method based on the analysis of responses given by persons (subjects) who observed test objects in controlled illumination conditions. The subjects were asked to state whether they could distinguish small details of the test object or not.

2.1. Test object

As a test object (visual stimulus) a square field covered with parallel black-and-white stripes of equal width was used. The stripes were printed on smooth silky paper with a high quality laser printer, which ensured their high contrast. The striped rectangle was located on a uniform white surface. The dimensions of the test object were 16×16 cm, so when viewed from the distance 4.25 m its angular size was 2°. The whole test was illuminated by light of different spectral characteristics. The following light sources were used:

– Halogen lamp emitting white light.

– Halogen lamp with red, green or blue broad-band absorption filters (GamColor©). The filters characteristics are presented in Fig. 1. The colours of lights obtained can be described by corresponding dominant wavelengths (λ = 625 nm, λ = 565 nm, λ = 475 nm).

– Sodium spectral lamp (λ = 589 nm).

– High pressure mercury lamp with interference filters (λ = 625 nm, λ = 588 nm, λ = 550 nm, λ = 475 nm, λ = 436 nm; half-width 10 nm).

– He-Ne laser (λ = 633 nm).

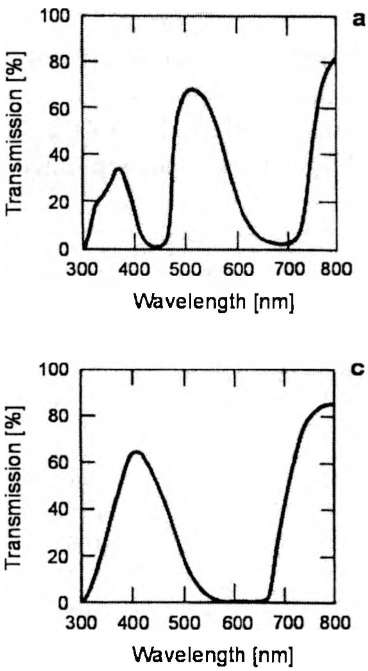

Fig. 1. Spectral characteristics of the GamColor© filters used: **a** – green ($T = 36\%$), **b** – red ($T = 7.7\%$), c – blue ($T = 4\%$).

The level of the test illumination was 300 lx in white light. In polychromatic light the illumination intensity was lower according to the filters transmittance (red filter $T = 7.7\%$, green filter $T = 36\%$, blue filter $T = 4\%$).

2.2. Procedure

The observer subjected to the test was seated in the dark room in the distance 4.25 m from the white background surface illuminated with coloured light of specified spectral characteristics. After few minutes of adaptation to the illumination conditions the test objects were presented to the subject who could observe them without any restrictions concerning the position of his head. A series of tests with increasing spatial frequencies were presented until the subject could notice the striped structure of the test. Alternatively, the tests of decreasing spatial frequencies were presented until the subject could see the uniform, grey field instead of the striped structure. The highest spatial frequency of the recognised test was recorded as the resolution limit.

The above procedure was repeated some 10 to 20 times and all the answers of the subject were recorded. The average value of the resolution limit and its standard deviation were calculated. All measurements were made in binocular vision. The orientation of the test was randomly changed in each measurement.

2.3. Subject

Eight subjects (persons): four females and four males, of different age took part in the experiments. Some of them were emmetrops, the others wore their correction glasses. All had normal colour vision. Their age and refraction data are collected in Tab. 1. In the same table the measured resolution limits in white light illumination are presented.

Table 1. Resolution limits in white light illumination.

Person	Age (in years)	Sex	R_x	MAR [arc min]	δ_{MAR}
B.D.	47	F	OP R_x = sph −2.75 dptr/cyl −1.25/90° OL R_x = sph −3.5 dptr/cyl −0.75/95°	1.32	0.061
D.K.	26	M	OP R_x = sph −2.5 dptr/cyl −1.25/20° OL R_x = sph −1.75 dptr/cyl −1.5/90°	1.62	0.050
A.M.		F	$R_x = 0$	1.57	0.078
K.M.	26	F	$R_x = 0$	0.98	0.045
Z.M.	50	M	OP R_x = sph −6.0 dptr/cyl −1.5/10° OL R_x = sph −5.75 dptr/cyl −1.75/170°	1.62	0.050
K.H.	26	F	$R_x = 0$	1.53	0.084
T.H.	25	M	$R_x = 0$	1.47	0.045
P.J.	24	M	$R_x = 0$	1.29	0.050

OP – right eye, OL – left eye

3. Second method

In the previous method a set of individual test objects of discrete spatial frequencies was used. In order to change the spatial frequency of the test, the person conducting the test has to perform some manipulations which distract the attention of the person subjected to the test. The finite differences between test spatial frequencies limit the measurement accuracy. Moreover, the striped structure has the rectangular profile containg higher harmonic components which might influence the result of the measurement.

In coherent light it is easy to develop an optical system generating periodic structure suitable for the measurement of visual resolution and free from these restrains [8]–[10].

3.1. Test object

As a test object an interference pattern generated in a laser interferometer can be used. Parallel equidistant fringes of a sinusoidal profile can be easily obtained in any type of interferometer. It seems that the three following types of interferometers: Twyman–Green, shearing and Wollaston type are especially useful for such aim. The sketch diagrams of these interferometers are presented in Figs. 2 **a**–**c**. In each case it is easy to change the spacing and orientation of the fringes observed on the screen by simple

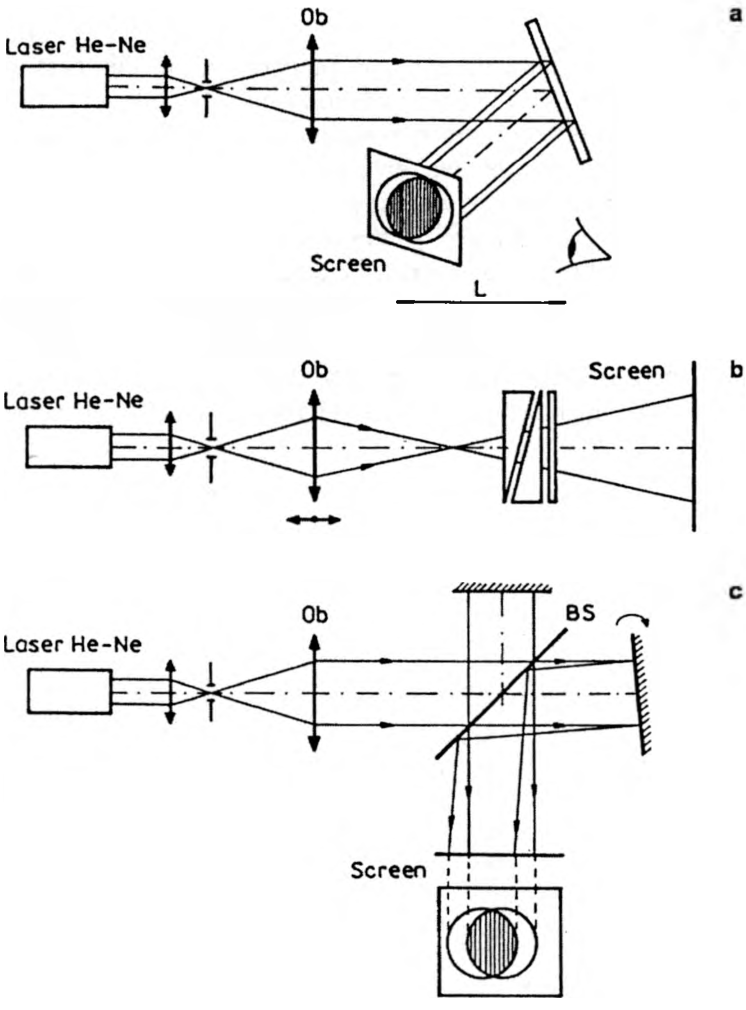

Fig. 2. Experimental set-up for interference fringes generation: **a** – shearing interferometer, **b** – interferometer with Wollastone prism, **c** – Twyman-Green interferometer.

movement of a single element. In particular, in shearing and Wollaston interferometers this can be done by shifting the collimating lens along the optical axis of the set-up. Slight bending of the fringes while changing the wavefront curvature of the light falling out the beam-splitting element does not disturb the measurement in practice.

The aperture of the interferometer was chosen in such a way that the diameter of the interference pattern created on a screen was about 15 cm (which corresponds to 2° as seen from the distance 4.25 m). Moreover, the fringed pattern has no sharp boundaries, and its average intensity falls down slightly to zero. Such situation is more convenient for the visual resolution measurement.

3.2. Procedure

The overall design of the experimental set-up and preparation of the person subjected to the test were the same as in the previous method. The subject could control the spacing of fringes generated on a screen by switching on and off the motor driving the movable part of the interferometer, or changing the direction of its movement. If the measurement started from very dense fringes, the subject was asked to increase their spacing until he could notice the fringes. Alternatively, the measurement started from fringes of very low spatial frequency and the person under test had to decrease their spacing until he could see the uniform light field. Both answers were recorded and the spatial frequency of "limiting" fringes was regarded as the resolution limit. Similarly as in the previous method the whole procedure was repeated 10–20 times and the average resolution limit and its standard deviation were calculated.

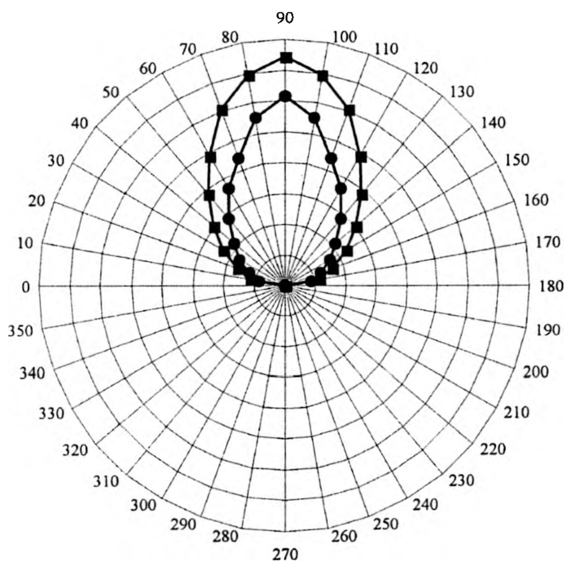

Fig. 3. Light diffusing directional characteristics (—●— ground glass of roughness #100, —■— ground glass of roughness #800).

In this measurement we wanted to check if there exists a direct relationship between the spatial resolution measured with interference fringes and the structure of the screen surface on which the fringes were observed. Three screen materials of different roughness were used: white silky paper and glass plate grinded with powder of different granularity #800 and #100 and covered with thin aluminum film (by vacuum evaporation). Light diffusing directional characteristics for ground glasses do not differ significantly (Fig. 3).

4. Results and conclusions

As the basis for further comparisons we adopted the resolution in white light. The results of measurements conducted on 8 subjects are presented in Tab. 1. The last two columns of this table refer to the resolution limit (MAR) and its standard deviations (δ_{MAR}).

4.1. Resolution in polychromatic light versus white light

Table 2 contains the data referring to the test illuminated by polychromatic light of a broad-band spectrum. Our intention was to compare the resolution in coloured light to the resolution in white light for the same subject with no regard to the absolute values. Therefore in respective columns we present the ratios of resolution limit in colour light and resolution limit in white light. Such normalised resolution is denoted MAR_{rel}. Values of standard deviation were calculated in a typical way. Since the number of our samples was not too great we used statistical methods for testing the significance of differences between mean values (*t*-Student test) on the level of significance 0.005 [11]. While comparing the data we can notice that for all person subjected to the test the resolution in blue light was significantly worse than in white light, but there is no significant difference in red and green light. The results of measurements are presented.

Table 2. Angular resolution MAR_{rel} in the light of broad-band spectrum.

	Red filter		Green filter		Blue filter	
Person	MAR_{rel}	δ_{MAR}	MAR_{rel}	δ_{MAR}	MAR_{rel}	δ_{MAR}
B.D.	1.03	0.082	0.98	0.050	1.39	0.122
D.K.	1.00	0.050	1.02	0.071	1.53	0.153
A.M.	1.18	0.107	1.14	0.050	1.20	0.082
K.M.	1.37	0.087	1.14	0.045	1.67	0.061
M.Z.	1.10	0.050	1.21	0.050	1.50	0.050
K.H.	0.96	0.045	0.93	0.071	1.06	0.050
T.H.	1.16	0.084	1.20	0.050	1.36	0.078
P.J.	1.00	0.050	1.00	0.050	1.26	0.050

4.2. Resolution in monochromatic versus white light

Table 3 contains the relative values of the resolution limit measured in monochromatic light as well as appropriate standard deviations. The statistical analysis of the presented data leads to the following conclusions:

– The resolution limit in blue light ($\lambda = 476$ nm, $\lambda = 436$ nm) is substantially worse than in white light (on the level of significance 0.005) for all subjects. For light of the

T a b l e 3. Angular resolution MAR_{rel} in monochromatic light.

Person	$\lambda = 625$ nm		$\lambda = 589$ nm		$\lambda = 588$ nm	
	MAR_{rel}	δ_{MAR}	MAR_{rel}	δ_{MAR}	MAR_{rel}	δ_{MAR}
B.D.	1.07	0.078	0.76	0.071	0.74	0.050
D.K.	0.99	0.045	1.01	0.078	1.02	0.090
A.M.	1.11	0.071	1.00	0.078	1.14	0.050
K.M.	1.32	0.050	1.15	0.050	1.32	0.050
M.Z.	1.00	0.050	0.93	0.078	0.90	0.050
K.H.	0.95	0.050	0.71	0.102	0.74	0.050
T.H.	1.06	0.082	0.93	0.084	1.21	0.050
P.J.	1.00	0.050	0.63	0.050	0.63	0.050

wavelength $\lambda = 436$ nm the average MAR_{rel} equals 1.8 so the decrease in the visual acuity in the blue end of the visible spectrum is almost 80%.

– It is difficult to find out the univocal tendency in green light. For the wavelength $\lambda = 550$ nm the resolution of two subjects is substantially worse than in white light ($MAR_{rel} > 1$), but for the other subjects the difference is not significant.

– In yellow light (in both sodium lamp $\lambda = 589$ nm and halogen lamp with interference filter $\lambda = 588$ nm) four subjects have substantially better resolution, the other two do not indicate substantial differences with respect to white light but one subject sees substantially worse. The average $MAR_{rel} = 0.9$, which means that irrespective of individual differences the visual acuity in yellow light is slightly better than in white light.

4.3. Resolution in coherent versus incoherent light

In the next experiment we wanted to check how the degree of light coherence influences the measured visual acuity. The same set of tests was used but the light illuminating the test was either incoherent (halogen lamp with interference filter) or coherent (He-Ne laser). The main wavelengths were practically identical ($\lambda = 625$ nm

T a b l e 4. Angle resolution MAR_{rel} in coherent and incoherent light.

Person	$\lambda = 625$ nm		$\lambda = 633$ nm (laser light)	
	MAR_{rel}	δ_{MAR}	MAR_{rel}	δ_{MAR}
B.D.	1.07	0.078	1.21	0.061
D.K.	0.99	0.045	0.97	0.078
A.M.	1.11	0.071	1.19	0.084
K.M.	1.32	0.050	1.37	0.078
M.Z.	1.00	0.050	1.18	0.145
K.H.	0.95	0.050	1.14	0.071
T.H.	1.06	0.082	1.19	0.071
P.J.	1.00	0.050	1.14	0.050

Tab. 3, continued.

$\lambda = 550$ nm		$\lambda = 475$ nm		$\lambda = 436$ nm	
MAR_{rel}	δ_{MAR}	MAR_{rel}	δ_{MAR}	MAR_{rel}	δ_{MAR}
1.04	0.084	1.38	0.135	2.01	0.105
1.14	0.114	1.41	0.157	1.96	0.105
1.13	0.045	1.22	0.061	1.82	0.141
1.15	0.050	1.81	0.050	1.98	0.050
1.13	0.078	1.67	0.122	2.02	0.071
0.95	0.050	0.93	0.071	1.36	0.107
0.99	0.050	1.29	0.078	1.41	0.071
1.00	0.050	1.25	0.050	1.76	0.050

and $\lambda = 633$ nm, respectively). The type of the surface did not influence the fringes contrast, which was verified using an objective method, namely, the analysis of the fringes image recorded by the CCD camera. The results of the visual resolution measurements are presented in Tab. 4, where the measured values of the resolution limit normalized to that in white light (MAR_{rel}) are presented for both illuminations. It can be easily seen that, except for one subject, the resolution limit in red incoherent light does not substantially differ from that in white light (average $MAR_{rel} \approx 1.0$), but in laser light the visual acuity is slightly but distinctly lower (average $MAR_{rel} \approx 1.1$).

Using laser light, we were able to measure the resolution limit basing on detection of sinusoidal fringes. In Table 5 we present the results of the resolution limit measurements done in the experimental set-up with the laser interferometer. The three sets of results refer to three screen surfaces of different roughness. The presented results do not suggest any clear tendency. Except for few particular cases, all results are very similar and it is not easy to find out any relationship between the state of the screen surface and the observed resolution limit. However, there is a general serious worsening of the visual acuity with respect to the resolution in white light. The

Table 5. Angular resolution for different screen granularities.

	Paper surface		Ground glass roughness #100		Ground glass roughness #800	
Person	MAR	δ_{MAR}	MAR	δ_{MAR}	MAR	δ_{MAR}
B.D.	2.17	1.0	2.12 ·	0.8	2.00	0.5
D.K.	2.38	1.7	2.38	1.3	2.24	1.0
A.M.	2.47	1.9	3.51	4.1	2.92	1.3
K.M.	1.97	1.0	2.37	1.3	2.44	0.9
M.Z.	2.24	0.9	2.50	1.0	2.58	1.5
K.H.	2.05	1.0	2.67	1.6	2.60	1.0
T.H.	2.23	0.9	2.53	0.9	2.41	1.1
P.J.	2.09	1.3	1.94	1.7	1.96	1.7

observed worsening of the resolution in laser light is probably caused by the specling effect. The character of speckles depends on two factors: statistical properties of the diffusing screen and the relative aperture of imaging system (the speckle size being inversely proportional to the aperture). It seems that in our experiment the average diameter of the eye pupil was so small that the influence of diffusing screen's diameter on speckle size was negligibly small in comparison to the influence of the pupil size. We plan to investigate this effect more precisely in the nearest future.

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