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Color Perception in Microgravity Conditions: The Results of CROMOS Parabolic Flight Experiment

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Abstract The aims of this research are first to verify the actual difference in color perception between conditions in Earth's ($1\times g$) and parabolic flight's microgravitational conditions (μg) and to improve the methodology used for data collection, testing the CROMOS software for color sensitivity investigation. Additionally this paper seeks to establish a larger awareness of microgravity vision and its design implications in the field of aerospace engineering. The analysis of variations in color perception between microgravity and $1\times g$ can be applied to a range of fields concerning the space habitat (Fig. 1), the design of information (such as safety notices), or in the space station the analysis of chemical and biological reactions based on chromatography (for example, when subtle color variations are used as indicators in histological cell analysis).

Forward: In September 2006, during the "ESA 9th Student Parabolic Flight Campaign" the CROMOS experiment collected new data to analyze possible differences between color perception in microgravity and normal gravity conditions. The student group received an award from Elgra in September 2007.

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Introduction

According to Mallowe (2001), in microgravity visual perception is of primary importance in perceiving signals for orientation because in weightlessness "people suppress vestibular signals and become increasingly dependent on vision to perceive motion and orientation" (Fig. 1).

As mentioned in the National Aeronautics and Space Administration's (NASA) requirements "Living Aloft": "Because of the importance of vision to the conduct of space missions, it was suggested in the early literature that the $0\times g$ environment could alter visual capabilities" (Connors et al. 1985).

Soviet investigators have expressed the opinion that vision in weightlessness is reliable and presents no obstacle to the conduct of space missions (Nicogossian and Parker 1982), nevertheless various studies demonstrate variations in color perception.

Kitayev-Smyk (1972) in an investigation on "achromatic and chromatic visual sensitivity during short periods of weightlessness", made in 1963 and published in 1972, found that brightness in relation to saturation increased in microgravity conditions. He noted illusions of varying duration, sometimes consisting in changes of color intensity, decrease of brightness and decrease in contrast. He attributed the phenomenon to an exaggerated motion of the retinal image. In a following study, again during short term weightlessness, he noticed that highly saturated yellow and red were

Fig. 1 Wide space and orientation. Color design study for Thales Alenia Spazio (Schlacht 2006; NASA Computer Image 1999)

perceived brighter, while blue was seen as less bright and mixed green (yellow/blue) was matched to yellow.

In White's (1965) results achromatic contrast sensitivity increased during parabolic flight, to a larger degree when colors were saturated.

Popov and Boyko's (1967) results demonstrated, amongst other things, that chromatic vision is strongly dependant on color adaptation and simultaneous and subsequent contrast. Tests were conducted in 1967 from which an average of 26.1% of subjectively perceived brightness reduction was found, more for purple, cyan (up to 50%) and green colors, less for red.

Table 1 Main results on color perception in microgravity

	Kitayev-Smyk 1972 [4]				White, 1975 [8]	Kravkov 1951 [9]	Popov-Boyko 1967 [10]	
Condition	Parabolic flight				Parabolic flight		Parabolic flight	
Instrument	Colorimetric table, ASR Spectroanomaloscope						Special colored table	
Target	28 people				198people		2 pilots	
changing	20 people						all	
Parameter + increased - decreased	**Brightness**		**Contrast sensitivity**		**Contrast sensitivity**		**Brightness**	
High intensity	*Saturation*		***0g*** *µg*	***1.8g*** *Hyperg.*	Contrast sensitivity increased	Color sensitivity increased	*Weightlessness condition*	
	High	*Low*						
Yellow	+++ More bright	- bright	++	--			Purple	-35/45 %
Green	- Less bright	- bright	+/- Not defined	-/+ Not defined			Green	-22/28 %
Red	++ More bright	- bright	+	-			Red	
Blue	+ Smallest Bright increase	- bright	-	+			Cyan	-43/48 %
Middle intensity						No changes		
Low intensity	Brightness decreased					Color sensitivity decreased		
Cause	Dilatation of retinal vessels under weightlessness condition							

Turning to astronauts' experience, ten out of ten astronauts interviewed by Schlacht for Thales Alenia (2005–2006) did not remember any consistent change in color perception, which suggested that an investigation needed to be very focused to have relevant results.

To date, studies on color perception in microgravity (Table 1) not using contemporary techniques (in fact they are mainly made in the 1960s), do not clearly define data collection, utilize different research methodologies, and are difficult to compare (Wise and Wise 1988). Therefore, further experiments using new methodologies are needed.

In the context of long duration space missions (eg. 3 years mission to Mars), the human factors related to this minimal difference in perception may become, in our opinion, a key factor for the well-being and productivity of astronauts (Schlacht et al. 2006).

The CROMOS Experiment

The setup for the CROMOS Experiment was based around a normal laptop upon which the CROMOS program ran. In order to reduce environmental influence, the video output was connected to a visor (virtual reality eyeglasses manufactured by eMagin®) that had a 640 × 480 pixel resolution and 24 bit color depth. The program, written by Stefano Brambillasca, was controlled by the use of a joystick such that the whole experiment could be made autonomously from the tester once the program was running. Feasibility and ease of use were important factors for the design of the experiment under weightlessness conditions. (The complete in-flight setup is shown in Fig. 2).

The experiment's goal was to verify possible variations in the sensitivity towards the color dimensions of chromatics, luminosity and saturation, and was based on the primary colors light of (Fig. 3): red, green and blue [R G B]. It was divided into four tests using the

Fig. 2 Experiment set up inside the Airbus A300, microgravity (*left*) and $1\times g$ (*right*)

visor monitor's RGB pixel values with a bit depth of eight for each color.

On starting the CROMOS program two colored squares were displayed, one on the right and one on the left (Fig. 4).

The left color is the target and the right color can vary by adjusting the RGB pixel intensity from 1 to 255 (Fig. 5). The subject used the joystick to modify the colors in the right square to match the target colors (on the left square) and record the range in which he perceived the two colors as identical. Kitayev-Smyk used a similar methodology with the 'Anomaloscope' based on light primary color mixing.

Following previous experiments' results (Table 1), we selected four colors to investigate: the colors analyzed were red (test 1) and blue (test 2) for chromatics, yellow (test 3) for saturation and gray (test 4) for brightness.

Conditions

Each test was performed in a lying posture using the same equipment in $1\times g$ and in microgravity. The microgravity experiment was performed in September 2006, on board the Zero G Airbus A300, during the European Space Agency (ESA) Ninth Student Parabolic Flight Campaign.

Normally, restrictions limited the experiments to the four students engaged in the experiment design. The CROMOS group (Fig. 6) had an ESA concession to fly with six students aged between 24 and 27, five males and one female. Each of the students had their color perception tested prior to the experiments using the standard pilots' vision check.

Four tests in microgravity were repeated twice for each subject (four tests × two times × six subjects), giving a total of 48 tests in microgravity compared to

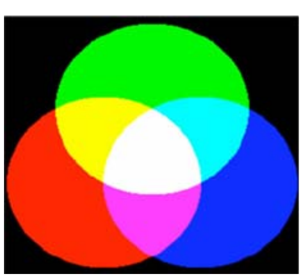


Fig. 3 RGB primary colors

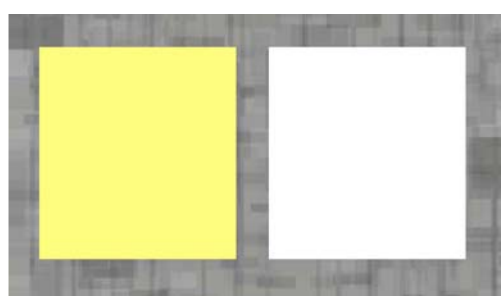


Fig. 4 Screen of test #3

	LEFT COLOR	RIGHT COLOR	
COLOR	**Reference Color**	**Start Adjustable Color**	**End Adjustable Color**
RED Test #1	Pure Red [255 0 0]	Yellow [255 255 0]	Magenta [255 0 255]
BLUE Test #2	Pure Blue [0 0 255]	Magenta [255 0 255]	Cyan [0 255 255]
YELLOW Test #3	Yellow 50% of saturation [255 255 128]	White [255 255 255]	Yellow [255 255 0]
GREY Test #4	Grey 50% brightness [128 128 128]	White [255 255 255]	Black [0 0 0]

Fig. 5 RGB values of the tests

720 tests at normal gravity. Each test was conducted in one parabolic flight (22 s). The 1.8×*g* hyper gravity preceding and following each 0×*g* parabola *might* have caused a bias. This was an unavoidable experimental condition (Fig. 7). It may be worth investigating whether this condition affects results; nevertheless, it is a common background factor throughout the trial.

Test subjects adopted the same horizontal posture on the ground and in flight to avoid possible erect-posture effects. Note that on ground, the conventional −6° bed rest posture (which is used to test for certain effects of microgravity) was not used. To do so would have created a comparison between a simulated microgravity and microgravity condition, not between 1×*g* and microgravity conditions.

Fig. 6 CROMOS team inside the flight 9.2006. From left to right; Prof. Masali M., Birke H., Schlacht I., Rotondi G., Brambillasca S., Vince M., Dianiska B.

As shown in the figures (Figs. 8, 9, 10, 11, 12, and 13), the data for subject 4 was incomplete because of sickness during the parabolic flight. To prevent weightlessness sickness subjects 4 and 6 took nautamine (diphenhydramine diacefyllinate 90 mg); subjects 1, 2 and 3 took Scopace (scopolamine hydrobromide 0.4 mg) and subject 5 did not take any medicine against motion sickness. We note here that scopolamine may introduce a negligable possibility of pupil dilatation.

Experiment Visualization

The visor's monitor exhibited a gray background called a *Mondrian patchwork*, used to reduce background-influences and ameliorate color vision, in visual investigations (Fig. 4).

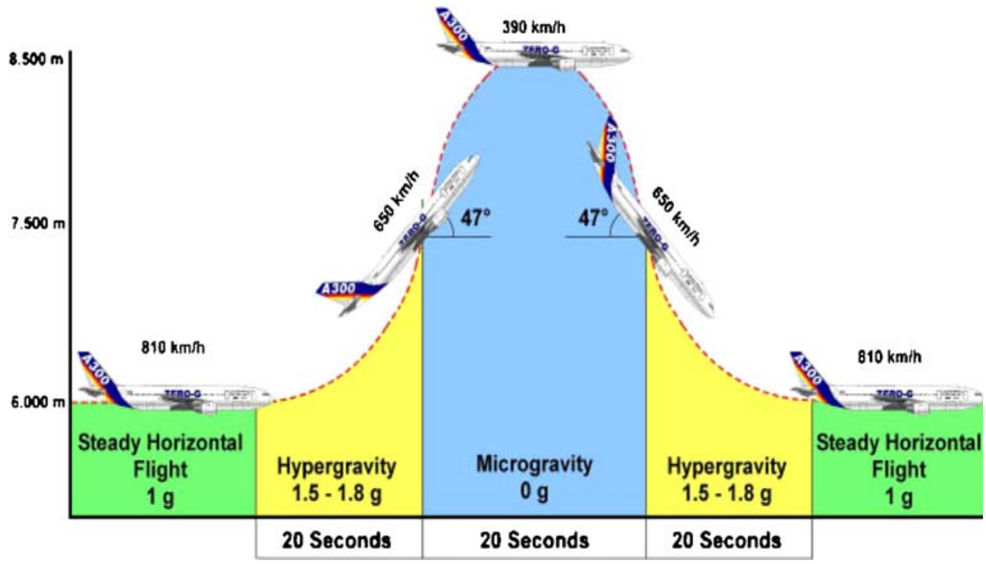
Test 1: red hue. The first test, to investigate the hue color dimension, set red [255 0 0] as "target color", while the adjustable color could be modified from yellow [255 255 0] to magenta [255 0 255] (Fig. 14).

Test 2: blue hue. In the second test, blue [0 0 255] is the "target color". The color modifiable by the subject was set up to start from magenta [255 0 255] up to cyan [0 255 255].

Test 3: yellow saturation. The third test, following Kitayev's investigation (Table 1), used yellow to investigate changing saturation sensitivity in microgravity. The reference used is the hue, saturation, value color model where the 0% saturation corresponds to white [255 255 255]. The target is yellow saturated at 50% [255 255 128]. The adjustable color can vary from 0% saturation (white) to yellow 100% saturation [255 255 0].

Test 4: Grey luminosity. In the fourth test, luminosity was studied by varying the values of all the three RGB pixel values. The target is to identify gray at 50% of luminosity [125 125 125]. The adjustable color varies from white [255 255 255] to black [0 0 0].

Fig. 7 Parabolic flight sequence



Test Procedure

In each test two points where selected to determinate the range in which the two colored squares were perceived equal: the "start point of the equality" and the "final point of equality".

Here, test 3 is presented as an example to describe and explain the tests' procedure.

Steps of Test 3

Test 3 performed in 20 s in microgravity and $1 \times g$.

Target color: yellow 50% of saturation [255 255 128]
Adjustable color: from white [255 255 255] to yellow 100% of saturation [255 255 0].

Step 1: pushing the joystick to the right the adjustable color [255 255 255] decreased the B value and consequentially increased the similarity with the yellow target [255 255 128].

Step 2: When the two colors were indistinguishable, the tester pressed the joystick button to record the RGB values at the "*start point of equality*".

Step 3: By continuing to push the joystick to the right the adjustable color will reach the target Yellow [255 255 128] (B value: 128), again continuing to push the joystick to the right B value decrease, until white [255 255 255] (B value: 0) was reached.

Step 4: The tester had to press the joystick button as soon he perceived the two colors as distinguishable. This recorded the RGB values of the "*end point of equality*".

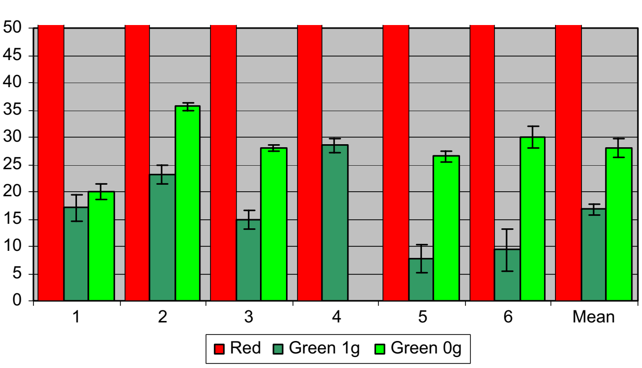


Fig. 8 Test ΔH_1

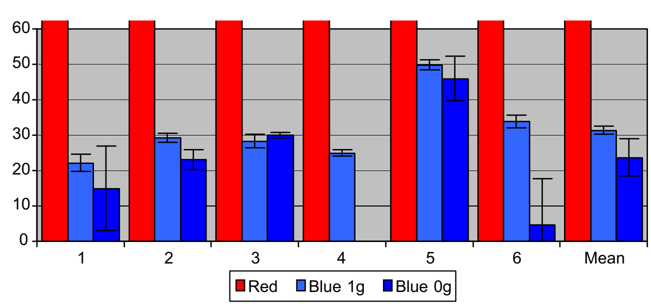


Fig. 9 Test 1 ΔH_2

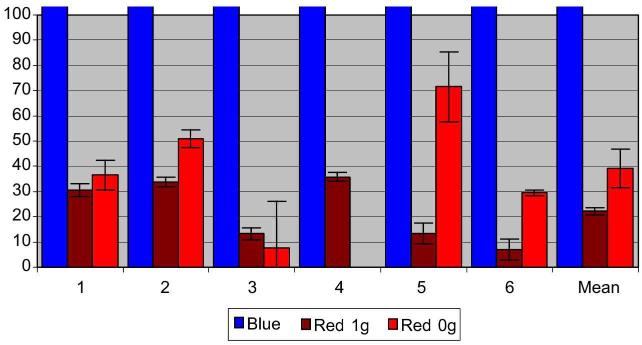


Fig. 10 Test2 ΔH_1

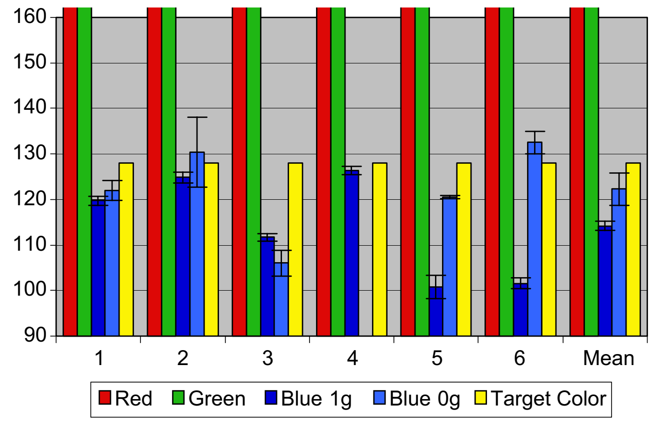


Fig. 12 Test3 ΔH_1

Methodology

The range of deviation of the "point of equality" from the target value was calculated for each test, therefore two deviations (ΔH_1, ΔH_2; Fig. 15) were calculated (Fig. 16).

ΔH_1 and ΔH_2 are found employing the equation:

$$|LeftR - RightR| + |LeftG - RightG| + |LeftB - RightB| = \Delta H$$

$$\text{LeftR, LeftG, LeftB} = \text{target color } [\text{R G B}] \text{ values}$$

$$\text{RightR, RightG, RightB} = \text{adjustable color } [\text{R G B}] \text{ values} \quad (1)$$

ΔH_1 is the difference between the "start point of equality" and the target color [R G B] values.

ΔH_2 is the difference between the "end point of equality" and the target color [R G B] values.

ΔH_1 ΔH_2 were calculated both for microgravity and in $1 \times g$.

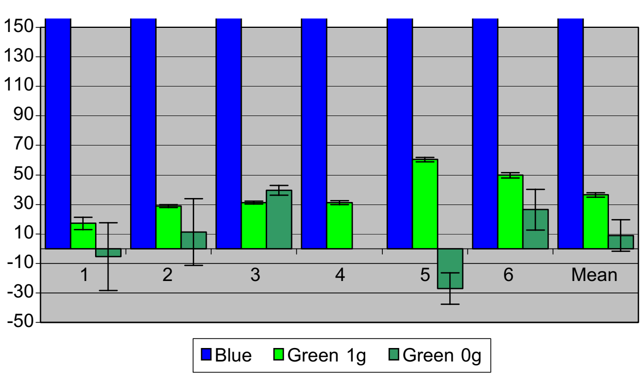


Fig. 11 Test2 ΔH_2

Each ΔH_1 ΔH_2 shows the influence of only one RGB variable on the target color (ex. In the test 3 only the B value is changing).

Previous studies had observed in weightlessness that the subjects perceived equal colors that in truth were different.

The CROMOS experiment found that $\Delta H^{1\times g}$ collected on the ground was different from $\Delta H^{0\times g}$ collected in weightlessness and we demonstrated that there was an effective variation in the perception of the colors.

Results

The experiment measured the "range of colors equality": the range in which two colors are perceived the same.

The objective is to compare the results in microgravity and in $1 \times g$ and in microgravity. The goal is

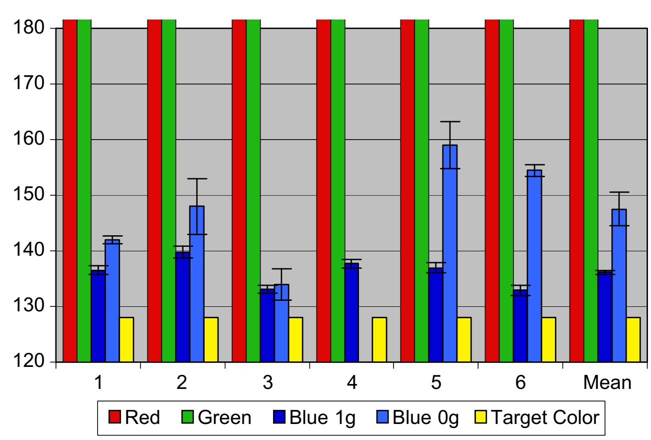
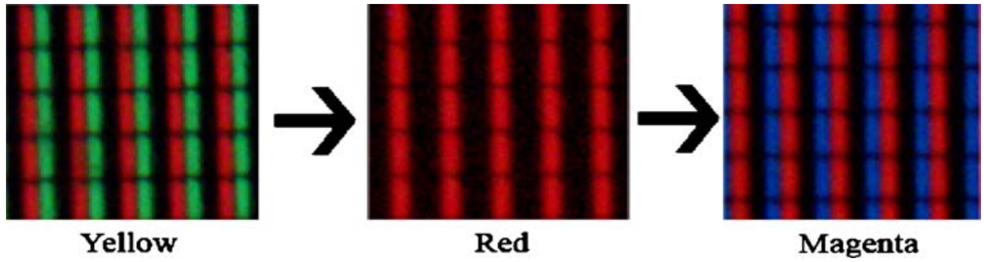


Fig. 13 Test3 ΔH_2

Fig. 14 Small section of the monitor showing how colors are modified by three types of diodes in test 1



to test the CROMOS software made to collect the experiment's data.

The results demonstrate strong coherency. Considering the variable of the parabolic flight and the subjects' first microgravity experience, a decreasing of the color sensitivity was expected in all the tests, with an increase in the "range of color equality". As shown in the results of test 4 the sensitivity at brightness decrease in microgravity (Fig. 17), while in tests 1, 2, 3 (Fig. 18) the "range of color equality" in microgravity is changing ranks and shifting on the left to different color values, demonstrating a perception change and not a sensitivity decrease.

The next diagrams show deviations obtained from each test. Seven groups of bars are displayed, the first six bars represent the six testers, and show the averages of the deviations from the target color; the seventh bar represents the mean average of the deviations for all the subjects.

Result test 1: red hue (perception: $-G$, $+B$)

In ΔH_1 only the G pixels were varied in the adjustable color (R = 255; G = 255 /0; B = off). In microgravity, the G pixels (as a component of the red color) were perceived as 4.4% less intense.

In ΔH_2 only the B pixels were varied ($R = 255$; G = off; B = 0/255). As we see from the graph, the deviation in perception of B, in most cases, was on average lower in microgravity. This meant that B (as a component of the red color) is perceived 3% more intensely in microgravity (Fig. 9).

Result test 2: blue hue (perception: $-R$, $+G$)

ΔH_1 in test 2 confirmed the outcome of ΔH_2 in test 1. In test 2 ΔH_1 equals (R = 255/0; B = 255; G =

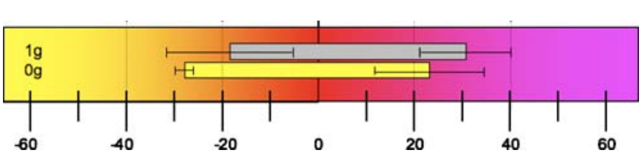


Fig. 15 Test 1 ΔH_1 (*left side*) and ΔH_2 (*right side*)

off). In microgravity there was an increase in the value for R pixels. This involved, a reduction of 6.6% in the perception of R intensity (as a component of the blue color).

This result (Fig. 10) confirmed previous results, because in both cases (test 1 ΔH_2 and test 2 ΔH_1) the perception of the B pixel is favored in respect to the R pixels.

In test 2 ΔH_2 (Fig. 11; $R = 0$; G = 0/255; $B = 255$). In microgravity, the G pixels (as a component of the blue color) were perceived as 10.8% more intense. In subjects 1 and 5 G values are negative (Fig. 11) because they selected the "end point of equality" *before* the "target color" was reached. One explanation, could be that the R pixels as component of the blue color were perceived as less intense.

Nonetheless, this would be a confirmation that hue color sensitivity increases in microgravity in the short wavelength (B) area of the visible spectrum and decreases in the long wavelength area (R).

Result test 3: Yellow saturation (in microgravity + saturated)

In ΔH_1 and ΔH_2 (R = 255; G = 255; B = 255/0). In microgravity (Figs. 12 and 13) B was perceived as slightly less intense (as a component of the yellow color).

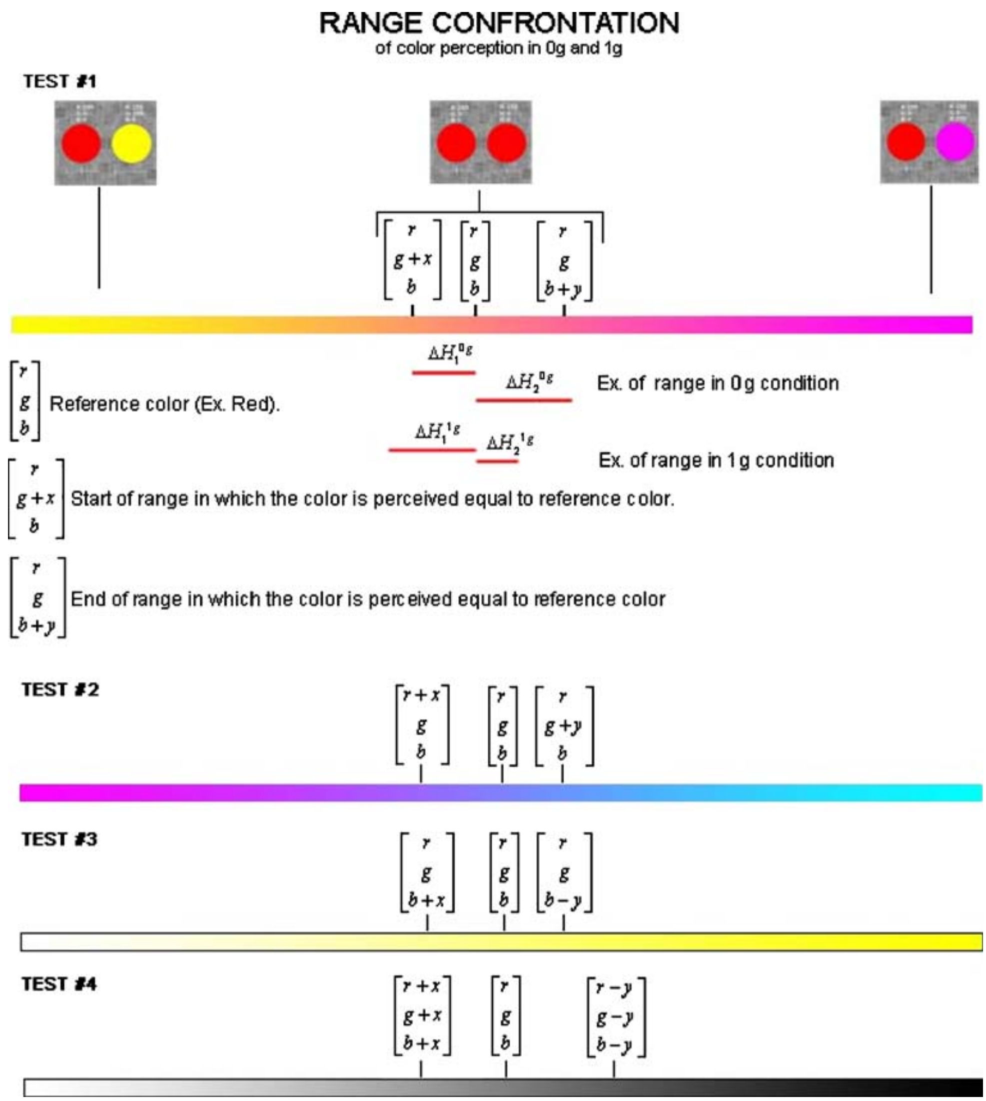
The total range of sensitivity in microgravity shifted, with almost the same amplitude of the $1 \times g$ values, towards white (saturation = 0), this means that yellow is perceived more saturated in microgravity with a shift of the mean value in a low saturation area of 2.9%.

Result test 4: brightness (in microgravity-sensitive)

The fourth test studied the variation of luminosity perception. Figure 17 shows that the range in microgravity is wider; this could be due to a general weakening of eye sensitivity to achromatic luminosity perception in microgravity.

In conclusion, while certain test results validate the results of Kitayev and White, others do not validate them, as in the blue case. In fact, following the

Fig. 16 Methodology for the result calculation



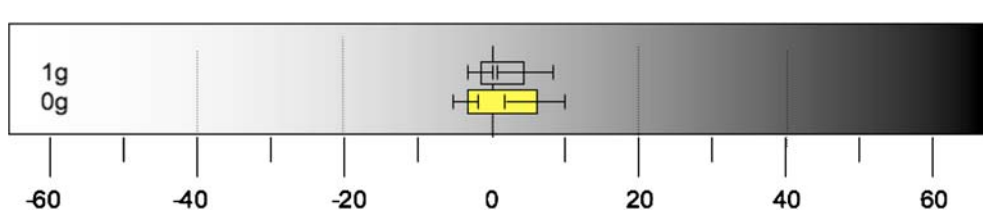
CROMOS' results it is perceived as more intense as in microgravity (Brambillasca et al. 2007).

Possible Causes of the Observed Effects

To understand the primary causes underlying the experiment it is necessary to study the human eye's biological characteristics. The two main eye structures are an optical system: the crystalline lens, and a sensitive system, that capture images and transmit them to the brain: the retina with its cones and rods.

There are three types of cones, which are present in various percentages within the eye. Each type has a peak sensitivity focused on a specific wavelength and has a different spectral response. Red cones are centered on 575 nm and are more abundant (64% of the total); Green cones are sensitive to 535 nm, and represent 32% of the total and have a higher spectral response. Blue cones are centered on 445 nm and

Fig. 17 Result test 4



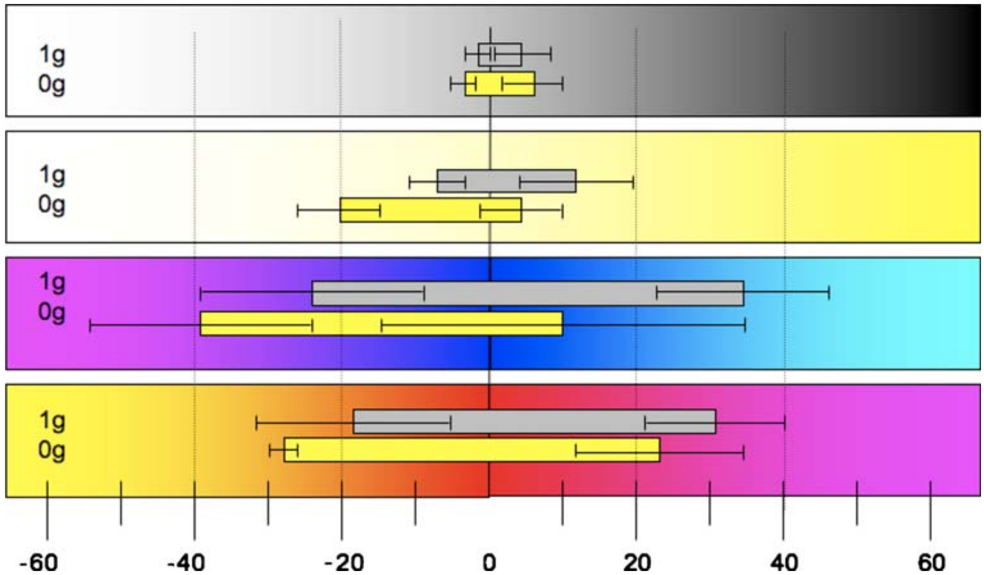


Fig. 18 CROMOS result. Mean value of deviation from "equal color" and RMS-value of the function [Color description for black and white print. From the *bottom* to the *top*: Test1 (−60: *yellow*; 0: *red*; 60: *magenta*); test 2 (−60: *magenta*; 0: *blue*; 60: *cyan*); test 3 (−60: *white*; 0: *light yellow*; 60: *yellow*); test 4 (−60: *white*; 0: *grey*; 60: *black*]. Because all results show a data shift in the same direction a further experiment is required, reversing the color sequence, to the test inferences

are only 2% of the total. The distribution of these cells is also instructive: if we represent the retina as a circle, rods are not found in the center (the fovea) but are the only cells towards the circumference. The blue cones are distributed on wide area while red cones and green cones are concentrated into the fovea (Khouw N, http://www.colormatters.com/khouw.html; Maelicke 1990).

Taking into account retinal structure, two explanatory hypotheses can be put forward to account for the findings of the microgravity experiment.

Hypothesis 1: increased blood flow to the light sensor cells in weightless conditions causes an increase in the sensitivity of retinal components, but to differing degrees in each cell type.

Hypothesis 2: the crystalline lens plays a role in modifying chromatic aberration with changing of curvature in microgravity and consequently focuses images on a different part of the retina with different concentration of RGB receptors.

In detail: chromatic aberration in the crystalline lens causes varied focal lengths and refraction for different wavelengths, and the distance between these points increases with increased convexity of the crystalline lens. Because of weightlessness, the crystalline lens becomes more spherical; this spreads more light across the entire retina surface. As a result, taking into account their distribution, stimulation of Blue cones and rods should be increased. The proposed hypothesis is therefore consistent with the experiment's findings.

Conclusions and Future Developments

This experiment may first appear to diverge from the notion of "experiment programming", that is randomness, blindness, sample size and homogeneity, possibility to repeat, in other words to have all the opportunities to avoid the *Heisenberg's principle* bias. This cannot be applied in our case and, common with the case for all *in flight* space research, most experimental and observation circumstances in which the sample is highly restricted for practical reasons.

Bearing in mind problems of sample limits our experimental philosophy was to get the maximum from our single opportunity.

In this philosophy a high significance of statistical tests was not expected as the degrees of freedom of the experiment (*df*: 5–1 = 4) are limited to the four crew allowed by ESA. Nevertheless, as a special benefit due to unexpected circumstances, ESA allowed, at the last moment, two extra crew that acted as "controls" taking the crew number to six (one lost by weightlessness sickness).

Therefore the traditional *t* tests was not expected to give much information at such *df* level as it requires huge differences to show moderate significance (only test 1a is close to high significance and tests 3 ΔH_1 and 4 are close to significance following the paired-samples *t* test procedure that compares the means of two variables that represent the same group at different times). A non-parametric alternative of the *t* test may be the Wilcoxon signed-rank test, a procedure that detects differences in the distributions of two related variables, based on the sum of the ranks. If the two variables do not differ, the sum of the positive ranks will approximately equal the sum of the negative ranks, and this never occurs in the experiment, while small significance values (<0.05) that indicate that the two variables significantly differ in distribution result in four over 12 tests.

As all the variables show unequal sums of positive and negative ranks we can conclude that the experiment achieved its primary purpose. That is to verify a new methodology to investigate the hypothesis that the perception of the colors could be influenced by gravity. Our data demonstrates a relationship exists and can be measured. Consequently, further experiments should be performed to analyze color perceptions variations.

Developments will be presented online on the Extreme Design group website: www.extreme-design.eu.

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