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A Four-Dimensional Spherical Model of Interaction Between Color and Emotional Semantics

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Background. The color and emotional systems are classical research objects in psychology and cognitive neuroscience, but the interrelations between them, especially at the semantic level, are poorly understood. The multidimensional approach, developed in E.N. Sokolov's "vector psychophysiology" school of thought, permits the solution of this important problem.

Objective. To carry out a psychophysical study of the interaction between color and emotions at the semantic level, through the analysis of subjective multidimensional spaces.

Design. The stimuli were the Russian names of 10 basic colors and 10 basic emotions. 102 participants used a scale from 1 to 9 to evaluate subjective differences in all possible combinations of color–color, emotion–emotion, and color–emotion. A 10×10 color submatrix, 10×10 emotion submatrix, and 20×20 full color–emotion matrix were processed by multidimensional scaling.

Results. The subjective spaces extracted from the color and emotion submatrices were found to be four-dimensional and spherical. The model of color semantics features two chromatic ("Red-Green" and "Blue-Yellow") and two achromatic ("Semantic Brightness" and "Contrast Grey") opponent axes. The model of emotional semantics features two basic ("Valence" and "Arousal") and two social ("Dominance" and "Social Rejection") opponent axes. The integral color-emotional space also was found to be four-dimensional and spherical, featuring combined color-emotional axes.

Conclusion. The interaction between color and emotional semantics can be described with a four-dimensional spherical model, proving that E.N. Sokolov's universal spherical model can adequately describe the processes of intermodal integration at the semantic level.

Keywords:
color, emotion, semantics, multidimensional scaling, spherical model, affective circumplex, vector psychophysiology

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Introduction

Two important domains of the human mind, emotion and color, have taken different evolutionary paths but can interact in their development, both phylogenetic and ontogenetic. Emotions can be regarded as a universal mechanism of integral assessment of the effect that the internal and external environment has on the realization of subject's needs (Simonov, 1997). The emotions acquire the function of a global low-differentiation assessment (Mehrabian & Russell, 1974), by contrast with a high-differentiation cognitive assessment. Trichromatic vision (Hiramatsu, Melin, Allen, Dubuc, & Higham, 2017), which formed in primates as a component of an evolving system of high-differentiation local cognitive assessment of the environment, is incorporated into the low-differentiation system of global emotional assessment of their mammal predecessors. A verbal system forms in the process of anthropogenesis and genesis of culture, so that color and emotions as individual mental domains, along with their interaction (the incorporation of colors into emotional assessment) have their effect on the verbal level, leading to the formation of color and emotion semantics and a system of color–emotion semantic associations. The functioning of such a system is an important problem of psychology and cognitive neuroscience. In our study, we were inspired by the multidimensional approach to cognitive neuroscience (E.N. Sokolov's "vector psychophysiology" school of thought, based on a universal spherical neuroinformational model).

Few studies have focused directly on color–emotion interaction. Hemphill (1996) used direct verbal associations and showed that the brightness scale is related to the hedonistic emotional scale. Zentner's (2001) work on the ontogenesis of color–emotion associations confirmed the relationship between emotional pleasure and brightness. Sutton and Altarriba (2016) showed associations between negative emotions and the colors red and black, and Hupka, Zaleski, Otto, Reidl, and Tarabrina (1997) showed similar associations in a cross-cultural study. Terwogt and Hoeksma (1995) used real colors and facial expressions of emotion and found that color–emotion preferences in adults showed no significant correlation with those in children.

Ou, Luo, Woodcock, and Wright (2004a, 2004b) used scaling of real colors in 10 "color–emotion" scales, corresponding to Osgood's three factors. A three-dimensional model was constructed: color activity, color weight, and color heat. They used a small sample to examine not separate color stimuli, but all their possible pair combinations, and factor analysis identified the same three factors. Gilbert, Fridlund, and Lucchina (2016) used a design in which the participants were to directly assign a color to each emotional term. They showed that emotions are significantly differentiated by all three color characteristics.

Of greatest interest for our study are the works of A. Mehrabian. First, in cooperation with J. Russell, he developed a three-dimensional model of emotions, Pleasure–Arousal–Dominance (PAD) (Mehrabian, 1996; Mehrabian & Russell, 1974; Russell & Mehrabian, 1977); second, he described the emotional characteristics of the real colors specified in the Munsell system by these three scales (Valdez & Mehrabian, 1994). Brightness was found to contribute most to the dimension of Pleasure, saturation to the dimension of Arousal, and brightness inversely contributes to the dimension of Dominance. Weaker regularities were found for hue. In the study of brightness and saturation, the differences between the stimuli under the PAD model are much greater than those in the study of hue. So, this study systematically examined the interaction of Munsell's characteristics (hue, value, and chroma) and emotions (PAD); however, a limitation of this approach was the lack of a full scheme of factor-to-factor interaction and the use of a predetermined system of emotional scales.

None of these studies considered multidimensional models of color and emotions in their potential interaction (except for that of Valdez and Mehrabian [1994], which, however, had the limitations described above). In our view, the method that can be used to solve this problem is Sokolov's vector psychophysiology approach (Sokolov, 2013). This is based on the construction of multidimensional models of mental processes with the use of multidimensional scaling of large above-threshold differences and their subsequent integration with multidimensional neurophysiological models. Vector psychophysiology uses a universal spherical neurocybernetic model of cognitive, affective, and motor processes (including elementary two-channel spherical modules of coding brightness, color, size, orientation, etc.). The biological background of Sokolov's model is formed by his analysis of information processes in real neuron networks in the brains of animals and humans and the development of an isomorphic model of cognitive architecture.

Sokolov's spherical model was empirically proved with the use of psychophysical and neurophysiological methods for color and emotions at both the perceptual and semantic levels (color perception: Izmailov & Sokolov, 1991; Sokolov, 2000; color semantic: Izmailov & Sokolov, 1992; emotion perception: Sokolov & Boucsein, 2000; Boucsein, Schaefer, Sokolov, Schröder, & Furedy, 2001; Izmailov, Korshunova, & Sokolov, 2005; emotion semantic: Izmailov, Korshunova, & Sokolov, 2008). However, with this approach, no model of interaction between color and emotions was constructed based on earlier separate models of color and emotions. In our view, such a formulation of the problem, implying the construction of a model of interaction between color and emotions and based on separate models of color and emotions, will not have the drawbacks of the previous studies that used other experimental paradigms (e.g., Valdez & Mehrabian, 1994).

We propose a new method for constructing a model of the interaction between color and emotions, based on unifying the subjective scales of color–color, emotion–emotion, and color–emotion differences. First, we propose to use the basic names of colors and emotions, rather than real colors and facial expressions. This is because Sokolov's vector psychophysiology studies showed that the subjective space of the names of basic colors is four-dimensional and spherical and essentially isomorphic to the subjective space of real basic colors, and the subjective space of the names of basic emotions is also four-dimensional and spherical and also essentially isomorphic to the subjective space of real facial expressions (Sokolov, 2013). Therefore, the difference between semantic stimuli will correspond to the difference between the same stimuli represented as real colors or as facial expressions. Second, the transformation of stimulation into a unified semantic format allows the participant to more easily compare the colors and emotions with one another (i.e., to compare words with words, rather than real colors with facial expressions). Third, based on the above reasoning, we propose a uniform scale of subjective differences, whereby the participant, in the subjective scaling of differences in pairs of words denoting color–color, emotion–emotion, or color–emotion, uses the same uniform scale (e.g., 1 to 9), rather than three different scales. This uniform scale can potentially actualize the implicit color–emotion relationships, thus enabling their measurement and analysis. We have successfully tested this approach in pilot experiments (Kiselnikov et al., 2016a, 2016b).

Methods

Stimuli. The stimuli were the Russian names of the 10 basic emotions (the set of six basic emotions according to P. Ekman (Ekman, 1999): *happiness, surprise, fear, sadness, disgust, and anger,* expanded according to Izard's classification (Izard, 1991) with the words *calmness, shame, contempt, interest*) and 10 basic colors (seven spectral chromatic colors: *red, orange, yellow, green, sky-blue, blue,* and *violet*, and three achromatic colors: *white, grey*, and *black*) (Russian original stimuli for emotions: *радость, удивление, страх, печаль, отвращение, гнев, спокойствие, стыд, презрение, интерес*; for colors: *красный, оранжевый, жёлтый, зелёный, голубой, синий, фиолетовый, белый, серый, чёрный*). Altogether, there were 20 stimuli (the names of 10 emotions and 10 colors).

Experimental procedure. Each stimulus was presented as a slide against a black background with a resolution of 1366 by 768 pixels on a 15.6″ laptop screen, using specially developed software, VectScal "Multidimensional Scaling of Visual Stimuli". The text of each slide was written in the monospaced Lucida Console font. In the experimental procedure, the participant had to assess the difference between all possible pairs of words ("emotion–emotion", "emotion–color", "color–emotion", and "color–color"). The participants were instructed before the experiment and then the first word was shown on the screen, followed by the second word. The participants had to give a subjective estimate of the difference between the current stimulus and that shown before, on a scale from 1 (minimal difference) to 9 (maximal difference). The current stimulus remained on the screen until the participant responded. Once the difference between the current and previous stimuli was given, the next stimulus was presented and remained until the participant responded.

Each series included the presentation of all possible pairs of stimuli from the matrix (a total of $20^*(20-1) = 380$ estimates of differences). Each participant took part in five experimental series, in which each of them gave a total of 1,900 estimates assessments of the difference between the stimuli. Prior to the main study, the participants subject took part in a trial series containing 190 comparisons (to actualize the associative connections between the stimuli and to form an appropriate scale of subjective differences), which was not included in the data.

The participants. The sample included 102 participants, native speakers of Russian (52 females), with an average age of 22.9 ± 3.7 (17–36) years. All participants had at least secondary-level education and normal or corrected to normal vision and color perception.

Data processing. The results of study for each participant were averaged over all five series to obtain a 20*20 matrix. After that, all these matrices for the 102 participants were averaged to yield the final matrix. To check the symmetry of the estimates in terms of the order of stimuli in pairs of the type A-B and B-A (where A and B are words from the set of 20 stimuli), correlation was calculated for the top and bottom triangular submatrices. The high correlation coefficient obtained shows the process of assessing the differences between stimuli to be symmetrical and allows averaging the matrix, relative to its diagonal, to obtain a symmetrical matrix suitable for multidimensional scaling. After that, two symmetrical color and emotional 10*10 submatrices were extracted from the symmetrical 20*20 matrix. Each of the three matrices was processed by multidimensional scaling with the Proxscal module in the SPSS 19.0 statistical package, with interval and ordinal transformation of proximities and a Euclidian metric. After making a decision regarding the dimensionality of each of the three spaces, we used an iterative procedure to find the center of the sphere maximally equidistant from all stimuli points. Thus, the stimuli points lie within a spherical layer with a thickness determined by some deviation from the radius of the sphere. The sphericity of the model was evaluated by the "coefficient of deviation from sphericity" (CDS), calculated as the ratio of the standard deviation to the mean radius. The configuration of points can be acceptably approximated by a sphere if the CDS does not exceed 10–15% (Izmailov & Sokolov, 1992; Paramei, Izmailov, & Sokolov, 1991; Sokolov, 2013).

If the sphericity hypothesis is accepted, the center of coordinates is placed in the center of the sphere and the configuration obtained is subjected to orthogonal rotation, following the literature on the nature of the axes of color and emotion spaces (Posner, Russell, & Peterson, 2005; Sokolov, 2013). Multidimensional scaling with transformation of proximities by an interval scale was used for parallel analysis of the stress curves obtained for color, emotional, and integral spaces, and nonmetric multidimensional scaling (the transformation of proximities by an ordinal scale) was used for the separate, more precise, analysis of the integral space.

Results

Table 1 gives the 20*20 matrix averaged over all runs of all participants.

Pearson's correlation coefficient between the top and bottom triangular submatrices was 0.988 ($p < 0.001$), allowing the matrix to be averaged relative to the diagonal. After interval multidimensional scaling and rotating, three models were constructed: one of color semantics, one of emotional semantics, and an integral model. Figure 1 gives the corresponding stress plots.

Table 1

*Matrix 20*20, averaged over the runs of all participants*

	anger	**interest**	**disgust**	**sadness**	**contempt**	**happiness**	**calmness**	**fear**	**shame**	**surprise**	**white**	**sky blue**	**yellow**	**green**	**red**	**orange**	**grey**	**blue**	**violet**	**black**
anger	0.00	7.06	3.91	5.88	4.05	7.66	8.13	4.37	4.91	6.67	7.27	7.54	6.37	7.42	3.09	5.50	6.44	6.89	5.90	3.88
interest	6.99	0.00	7.22	7.13	7.36	3.57	5.76	6.42	6.66	3.23	5.14	5.30	4.15	4.55	4.11	3.96	7.26	5.32	5.60	7.38
disgust	4.01	7.63	0.00	5.72	2.86	8.13	7.36	4.39	4.55	6.99	7.43	7.06	6.21	6.38	5.88	6.67	5.03	6.73	5.45	4.59
sadness	5.52	7.05	5.46	0.00	5.22	7.92	5.03	4.84	4.86	6.83	5.50	5.08	6.68	6.15	7.31	7.52	2.86	4.60	4.61	3.32
contempt	3.77	7.23	3.12	5.33	0.00	7.78	7.00	4.76	4.15	6.70	6.77	6.76	6.06	6.64	5.65	6.68	4.72	6.59	5.44	3.90
happiness	7.67	3.75	7.97	8.10	7.93	0.00	5.21	7.69	7.70	3.67	4.51	4.73	3.32	4.70	3.57	3.26	7.57	5.94	6.25	7.91
calmness	8.16	5.65	7.57	4.82	7.10	5.08	0.00	7.68	7.31	6.52	2.53	2.90	6.16	3.76	7.44	6.85	3.75	3.44	5.15	6.25
fear	4.51	6.59	4.71	5.04	4.80	7.56	7.69	0.00	4.12	6.41	6.61	6.86	6.36	6.99	5.16	6.77	4.89	6.47	5.43	3.63
shame	4.86	6.91	4.31	5.26	4.61	7.47	7.13	4.45	0.00	6.66	6.48	6.39	5.80	6.89	4.47	6.41	4.98	6.14	5.72	4.42
surprise	6.46	3.40	6.73	7.09	6.63	3.50	6.24	6.08	6.58	0.00	5.58	5.57	4.71	4.98	4.86	4.19	7.38	5.72	5.60	7.32
white	7.32	5.29	7.26	5.20	6.90	4.65	2.90	6.72	6.61	5.72	0.00	3.66	4.43	5.88	6.69	6.16	3.53	5.29	6.57	7.50
sky blue	7.36	4.82	6.87	4.68	6.63	5.10	2.98	6.69	6.49	5.57	3.73	0.00	5.88	4.44	6.58	6.51	4.31	2.34	4.18	6.55
yellow	6.31	4.27	5.79	6.44	5.88	3.40	6.10	6.31	5.38	4.53	4.72	5.90	0.00	4.49	3.96	2.55	6.33	6.18	6.51	6.91
green	7.25	4.71	6.39	6.04	6.48	4.75	3.84	6.94	6.45	5.21	5.77	4.28	4.41	0.00	6.42	5.75	6.05	4.26	5.79	6.35
red	3.04	4.25	5.78	7.08	5.81	3.77	7.66	5.06	4.93	4.91	6.52	6.89	3.78	6.56	0.00	2.73	6.84	6.67	4.78	6.14
orange	5.56	4.03	6.33	7.45	6.50	3.34	6.54	6.64	6.10	4.27	6.21	6.40	2.63	5.98	2.74	0.00	7.01	6.79	6.32	7.02
grey	6.02	7.00	4.98	3.06	4.60	7.29	4.18	4.92	5.13	7.17	3.52	4.43	6.29	6.03	7.14	7.09	0.00	4.81	5.82	3.30
blue	7.04	5.42	6.41	4.74	6.15	5.54	3.61	6.26	6.43	5.79	5.46	2.32	6.32	4.42	6.51	6.68	4.72	0.00	3.56	4.38
violet	6.01	5.76	5.72	5.11	5.45	6.15	5.48	5.73	5.59	5.78	6.67	4.01	6.53	5.98	4.86	6.28	6.11	3.51	0.00	4.77
black	3.93	7.42	4.36	3.49	4.36	8.16	6.33	3.49	4.82	7.37	7.72	7.00	7.15	6.92	6.08	7.24	2.95	4.80	4.76	0.00

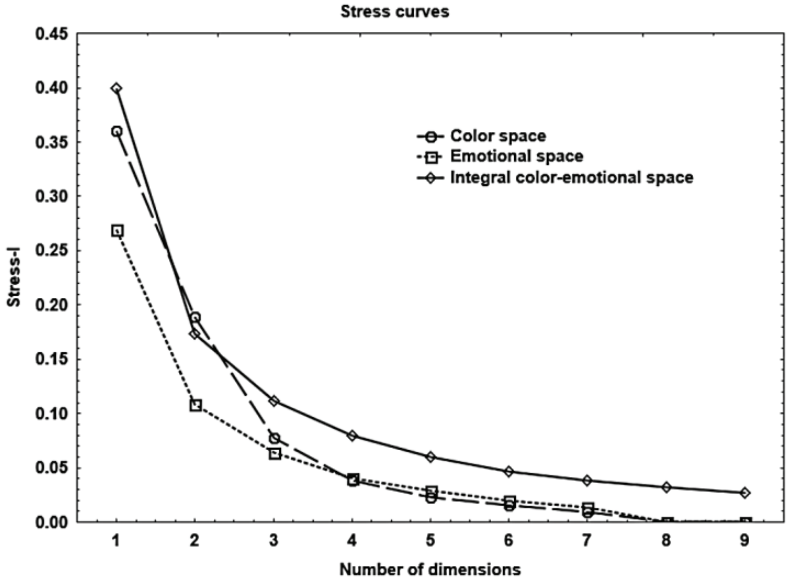

Figure 1. Stress curves

To more precisely identify the structure of the integral space, the 20*20 matrix was also processed by the method of nonmetric multidimensional scaling.

Based on the curvature of the scree plot and the threshold value of the stress, we decided to construct a four-dimensional model in each of the three cases. The CDS in each of the three models was found to be less than 8% (for color = 6.4%, for emotion = 7.12%, for color–emotion = 7.58%), suggesting that the stimuli lie close to the surface of the sphere of fixed radius. Tables 2, 3, and 4 give the coordinates of the four-dimensional solutions obtained after rotation.

Table 2

Coordinates of the four axes of the rotated color space (interval multidimensional scaling, stress I, Kruskal formula = 3.8%, coefficient of deviation from sphericity = 6.4%)

	X1	**X2**	**X3**	**X4**
white	–0.071	0.183	0.935	–0.511
sky blue	0.785	0.143	0.556	–0.212
yellow	–0.542	0.212	0.440	0.523
green	0.360	0.852	0.100	0.507
red	–0.369	–0.698	–0.129	0.563
orange	–0.470	–0.343	0.352	0.803
grey	–0.051	0.227	–0.022	–0.907
blue	0.879	0.235	–0.079	–0.177
violet	0.777	–0.573	–0.266	0.075
black	0.024	–0.011	–0.902	–0.558

Table 3

Coordinates of the four axes of the rotated emotional space (interval multidimensional scaling, stress I, Kruskal formula = 3.9%, coefficient of deviation from sphericity = 7.1%)

	X1	X2	X3	X4
anger	−0.836	0.545	0.178	−0.320
interest	0.795	0.347	−0.413	−0.185
disgust	−0.954	0.307	0.068	0.290
sadness	−0.513	−0.700	−0.227	−0.305
contempt	−0.857	0.074	0.247	0.168
happiness	1.074	0.237	0.035	0.111
calmness	0.568	−0.850	0.023	0.023
fear	−0.711	0.294	−0.550	−0.428
shame	−0.724	0.086	−0.629	0.305
surprise	0.622	0.614	−0.085	−0.028

Table 4

Coordinates of the four axes of the rotated integral color–emotion space (nonmetric multidimensional scaling, stress I, Kruskal formula = 8.0%, coefficient of deviation from sphericity = 7.6%)

	X1	X2	X3	X4
anger	−0.882	0.584	0.069	−0.286
interest	0.823	0.445	0.180	−0.431
disgust	−0.913	0.074	0.562	0.179
sadness	−0.445	−0.861	−0.182	−0.091
contempt	−0.832	0.047	0.402	0.425
happiness	1.008	0.449	−0.077	0.077
calmness	0.678	−0.859	−0.010	0.162
fear	−0.788	0.042	−0.523	−0.347
shame	−0.709	0.132	−0.369	0.453
surprise	0.635	0.489	−0.453	−0.430
white	0.640	−0.505	−0.442	0.450
sky blue	0.618	−0.672	0.096	−0.224
yellow	0.443	0.508	0.158	0.499
green	0.657	−0.218	0.732	0.211
red	−0.037	0.884	0.069	−0.163
orange	0.392	0.912	0.074	0.178
grey	−0.292	−0.817	−0.131	0.273
blue	0.341	−0.682	0.359	−0.447
violet	−0.094	−0.225	0.368	−0.774
black	−0.909	−0.436	0.094	−0.304

Discussion

Color semantic model. Figure 2 gives planes of the subjective space of color semantics formed by four bipolar axes.

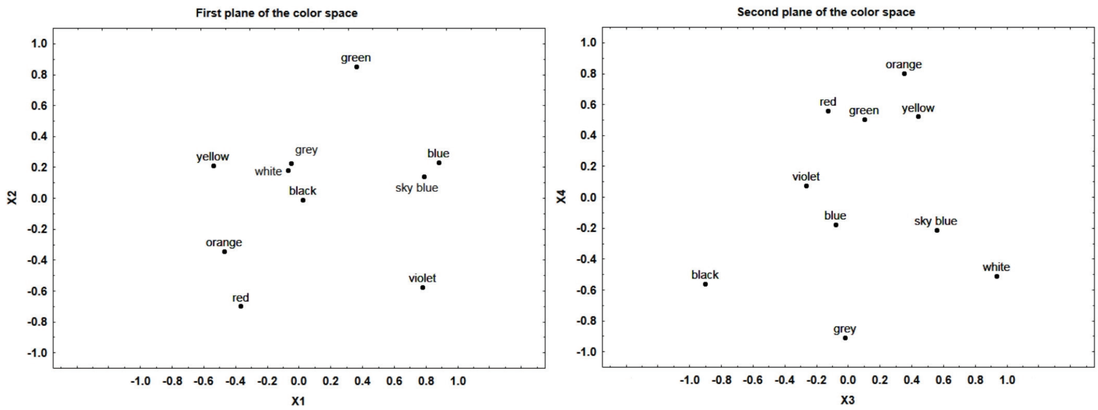

Figure 2. Subjective space of color semantics (left: a plane formed by the 1st and 2nd axes; right: a plane formed by the 3rd and 4th axes)

The first plane (axes 1 and 2), which is the plane of the hue, fully describes the configuration of colors with respect to one another. It shows the classical Newton circle (Izmailov & Sokolov, 1992), typical of subjective color spaces. The first axis of the color space is related to the classical opposition Blue–Yellow, the second axis to the opposition Red–Green, while the achromatic colors (black, grey, and white), as expected, occupy the center of the plane. The second plane (axes 3 and 4) is interpreted as the plane of Semantic Brightness and Contrast Grey. The third axis (Semantic Brightness) is organized such that black lies at the negative pole, while violet, red, blue, grey, and green lie nearer to zero; orange, yellow, and sky-blue lie further away, and white, the brightest color, occupies the positive pole. The fourth axis (Contrast Grey) has grey at the negative pole; the next colors are black and white; further away are sky-blue, blue, and violet; then green, yellow, and red; and at the positive pole orange, the color most opposed to grey. The fourth axis can be interpreted as a reflection of the activity of the "darkness neuron" at the semantic layer (see Sokolov, 2000, Fig. 3).

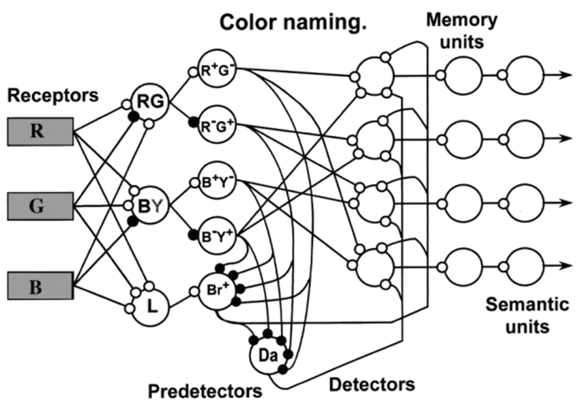

Figure 3. The network represents a local color analyzer supplemented by memory and semantic units (from Sokolov, 2000)

However, unlike in Sokolov's model, the fourth channel at the semantic level is not unipolar but opponent—i.e., the unipolar darkness neuron, tuned to grey, is opposed by a "contrast-grey neuron", tuned to orange.

The plane of saturation was constructed by a standard procedure developed in Sokolov's vector psychophysiology: 10 stimuli were distributed on a plane, the abscissa of which was the square root of the sum of the squares of the coordinates along the first and second axes, while the ordinate is the square root of the sum of the squares of the coordinates along the third and fourth axes (see Fig. 4), so saturation can be calculated as the angle between the planes of hue and brightness.

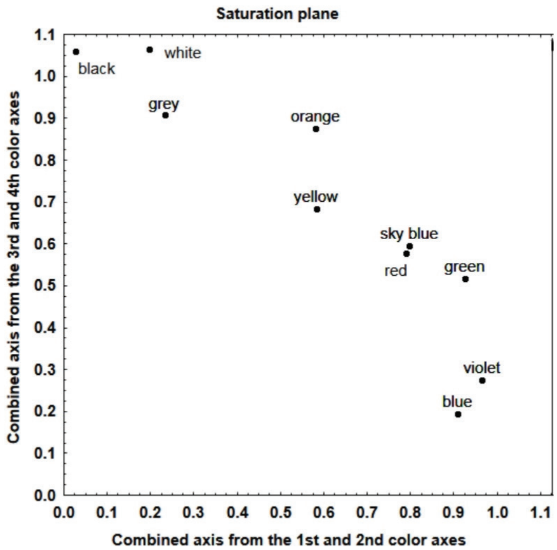

Figure 4. Saturation plane

As can be seen, the stimuli are located on a quarter of a circle (as predicted by Sokolov's spherical model), with saturation coded by the angle of deviation from the ordinate: Achromatic colors are the least saturated, and blue and violet are the most saturated. Note that saturation, if calculated like this, monotonically relates to but differs from the Brightness or Contrast Grey axes.

Emotion semantic model. Figure 5 gives the planes of the subjective space of emotional semantics formed by four axes.

The proposed model of emotional space is largely similar to the Russell circumplex model (Gerber et al., 2008; Yik, Russell, & Steiger, 2011) and the PAD model (Mehrabian & Russell, 1974; Valdez & Mehrabian, 1994); however, unlike the latter model, a fourth axis was identified.

The first plane is formed by the Valence and Arousal axes. The group of emotions at the negative pole of the Valence axis includes Disgust, Anger, Contempt, Shame, and Fear; further toward the center of the axis is the Sadness emotion. The emotions on the other side of the axis are Happiness, Interest, Surprise, and Calmness, among which Happiness is the most positive. The group of emotions at the negative pole of the Arousal axis includes Calmness and Sadness; the emotions on the positive pole are Anger and Surprise. We can see the classical configuration, corresponding to Russell's affective circumplex (Yik et al., 2011).

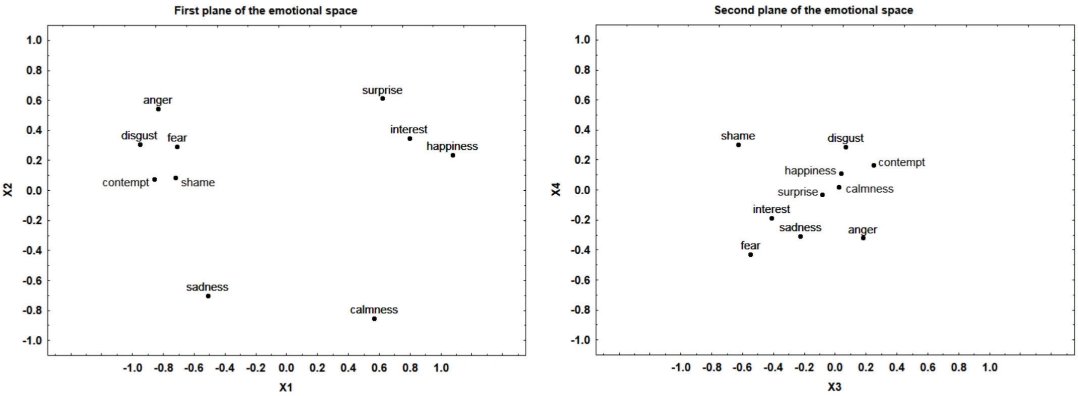

Figure 5. Subjective space of emotional semantics (left is the plane formed by the 1st and 2nd axes; right is the plane formed by the 3rd and 4th axes)

The axes on the second plane were interpreted as those of Dominance (vs. Submissiveness) and Social Rejection. The axes in this plane show much less variance (by about half) than those in the first plane. This may be attributed to the fact that the social aspect of these emotions, which is reflected by these axes, is secondary to the basic axes of Valence and Arousal. In the first plane, we see the basic projection of emotions, while the second plane shows separately the social aspects of the same emotions. The Dominance axis is formed by the opposition of the pairs of Anger and Contempt vs. Fear and Shame. The axis of Social Rejection is underlined by the opposition of the pairs of Contempt and Shame vs. Anger and Fear. The emotions of Anger and Fear are complementarily combined: Fear is the response of the subject to Anger directed against him. The emotions of Contempt and Shame are also complementarily combined: Shame is the response of the subject to Contempt directed against him. The passage from Fear to Shame and, in parallel, from Anger to Contempt, is accompanied by an increase in Social Rejection; Shame is associated with fear of social rejection, and Contempt is associated with Anger directed against the object of social rejection.

The plane of axes 1 and 2 is a "basic" plane, as the opponent axes described have a universal nature, common to humans and animals, coinciding with the Russell circumplex (Kuppens, Tuerlinckx, Russell, & Barrett, 2013; Kuppens et al., 2017; Yik et al., 2011), and have about twice the extent of the axes of the second plane. The plane of axes 3 and 4 can be referred to as "social" plane, because the oppositions described in it originate from the interaction of subjects in the field of social relationships (see also Landa et al., 2013). The Social Rejection axis, added to Dominance, makes the description of the social aspect of emotional functioning more complete.

Such division can be found in the literature on vector psychophysiology, where a model of elementary two-channel modules of coding various aspects of simulation is described (Sokolov, 2013). In that model, the processing of a complex stimulation is associated with simultaneous activation of several two-channel modules, the activity of which is coordinated according to a spherical law—i.e., for any two stimuli, the square root of the sum of the squares of their coordinates is a constant (the length of the radius-vector). The correctness of this approach was demonstrated for the perception of brightness, color, and orientation of visual stimulation (Sokolov, 2013). The model of emotional semantics we described can also be regarded as consisting of a pair of two-channel modules, one specialized in the coding of basic, universal emotional information, and the other in coding a more particular social aspect, and these two-channel modules are interrelated with one another by a spherical law (the CDS is 7.1%, i.e., below the threshold value of 10–15%).

Comparing our emotional model, based on names of emotions, with Sokolov's four-dimensional model, which is fundamental for us and which used schematic faces (Sokolov & Boucsein, 2000; Boucsein et al., 2001), it is apparent that the global four-dimensional spherical architecture of the subjective space is the same, although the individual axes and their interpretations are somewhat different. In Sokolov's model, the first plane ("emotional tone") is formed by two opponent axes Pleasure/Unpleasure and Fear/Anger, and the second plane ("emotional intensity") is formed by a unipolar axis of neutrality and an opponent axis Arousal/Dearousal (Fig. 6).

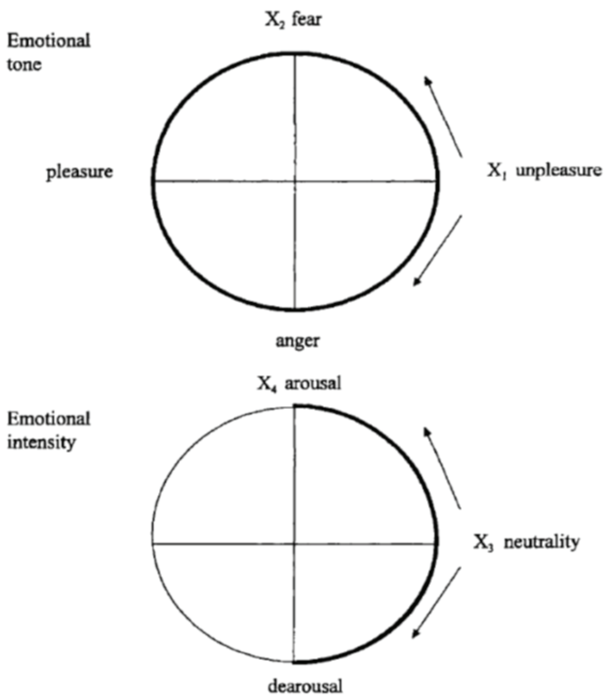

Figure 6. Model of emotional space from Sokolov and Boucsein (2000)

In our model, the first ("basic") plane is formed by two opponent axes, Valence and Arousal, and the second ("social") plane is formed by the opponent axis Dominance and the axis Social Rejection. An analogy can be established between Sokolov's Pleasure/Unpleasure and our Valence, between Fear/Anger and Dominance, and between Arousal/Dearousal and Arousal. Our model does not contain a unipolar axis of neutrality; instead we have Social Rejection.

Sokolov's model and the model we propose are systems of two two-channel modules interrelated by a spherical law; however, in Sokolov's model, these are the modules of emotional tone and emotional intensity, whereas in our model, these are the modules of basic and social emotionality. The difference between the models may be because the stimulation in Sokolov's model was represented by schematic faces, while our stimulation represented generalized emotional concepts. The passage from perceptual to semantic representation of emotions may be accompanied by some generalization, mediated by processes of social categorization and leading to a reduction of the axis of perceptual emotional neutrality and the actualization of a semantic axis of Social Rejection (however, the spherical mechanism of interrelation of the axes still functions). Another reason for the difference between the planes may be that the procedure of space rotation in the models was based on different conceptual criteria: Sokolov relied on an analogy with color space, while we used a comparison with Russell's circumplex model.

Integral model of color–emotion semantics. Figure 7 shows planes of integral subjective space, formed by four bipolar axes.

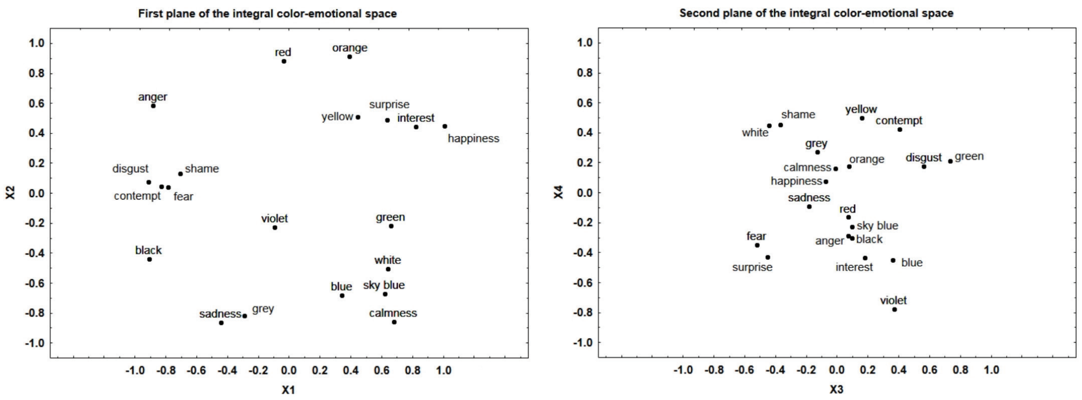

Figure 7. Subjective integral space of color–emotion semantics (left—the plane formed by the 1st and 2nd axes; right—the plane formed by the 3rd and 4th axes)

The first plane, as well as in the emotional space described above, is formed by Valence and Arousal. The first plane incorporates the color information from the two above planes of the color space—i.e., the integral color–emotion space is arranged primarily according to the emotional axes. This may be explained by the fact that the emotion evaluation system is more fundamental than the color system (Adams & Osgood, 1973). We can see a deformed Newton's circle inscribed into half of Russell's circumplex, formed by positive emotions (the first plane of the color space). This means that all chromatic colors are associated with positive emotions, with yellow and orange falling into the domain of active positive emotions; blue, sky-blue, and green are in the dearoused domain of positive emotions; red and violet were found to be rather emotionally neutral, and of these, red was found to be active, and violet was in the middle of the Arousal axis. White lay near the chromatic colors, while black and grey were in the emotionally negative part of the plane.

To describe the relationship of hue to Arousal and Valence, we consider the projection of Red–Green and Yellow–Blue into various domains of the integral space. The opposition of the red and green color characteristics is due to the opposition of the domain with neutral Valence and strong Arousal to the domain positive in Valence and moderately aroused. The opposition of the yellow and blue color characteristics is associated with the opposition of strongly and weakly aroused positive-Valence domains.

The deformation of Newton's circle may be associated, in particular, with the effect of information from the second plane of the color space—i.e., information about the Semantic Brightness and Contrast Grey characteristics of colors. Thus, the Valence on the first plane of the integral space nearly coincides with Semantic Brightness in such a manner that white, sky-blue, yellow, and orange are emotionally positive; grey, violet, and red are emotionally neutral; and black is emotionally negative. Arousal on the first plane of the integral space nearly coincides with Contrast Grey, such that the grey on the lower pole proves to be most unaroused; following it are black, blue, sky-blue, and white, followed by violet and green, with the most aroused being the colors on the upper pole—yellow, red, and orange.

Continuing the analysis of the first plane of the integral space, we can identify characteristic groups of stimuli, arranged along certain straight "isolines". Several "isoarousal" lines can be seen with stimuli in them not differing in Arousal but varying in Valence, along with several "isovalence" lines, which are orthogonal to the previous isolines and have stimuli not differing in Valence but varying in Arousal. All isoarousal lines are approximately parallel to the Valence, while all isovalence lines are approximately parallel to the Arousal. We can identify the following isoarousal lines (from dearousal to strong arousal): calm, grey, sadness; white, sky-blue, blue, black; green, violet, shame, fear, contempt, disgust; happiness, interest, surprise, yellow, anger; orange, red. Similarly, we can identify the following isovalence lines (from displeasure to pleasure): black, contempt, fear, disgust, shame, anger; sadness, grey, violet, red; blue, yellow, surprise, orange; calm, sky-blue, white, green, interest, happiness. We can see that the opposition blue vs. yellow is parallel to the isovalence lines, while the opposition red vs. green forms 45° angles with the isovalence and isoarousal lines, and the brightness opposition black vs. white is parallel to the isoarousal lines.

Let us analyze the second plane of the integral space (Fig. 7, right). The configuration of colors does not form either a systematic Newton's circle or axes of Semantic Brightness and Contrast Grey. This means that, as compared with the first plane, the color here is even more suppressed by the emotions. The configuration of emotions forms two orthogonal characteristics, which correspond to the previously identified Dominance and Social Rejection. On the positive pole of the Dominance axis is a cluster of semantic objects including disgust, contempt, green, blue, and violet; a lesser load falls onto the cluster including anger, red, yellow, orange, black, interest, and sky-blue, whereas the negative pole of the Dominance axis includes fear, surprise, white, and shame. On the positive pole of Social Rejection is a cluster of semantic objects that includes shame, contempt, white, and yellow; closer to the negative pole is the cluster of fear, black, anger, and sky-blue, while on the pole itself is the cluster of violet, blue, interest, and surprise. We can see that, moving from emotional to color-emotional stimulation, which potentially actualizes more diverse affective tones and oppositions, the axis of Social Rejection acquires a distinct opponent pole in the form of the emotions of interest and surprise. This agrees well with the behavioral interpretation of these emotions: social rejection and interest are opposing behavioral patterns.

Now let us compare our results with those of Adams and Osgood (1973), in which projections of the names of the basic colors into the space of Evaluation, Activity, and Potency were obtained in a large-scale cross-cultural study. Our data coincide with the data of that study in that black and grey are classified as emotionally negative colors, while white, blue, and green are emotionally positive; black and grey are nonactivated colors, and red is activated; the scale white–grey–black is close to the Evaluation axis. Deep analysis of the distribution of points suggests some inverse relation between Osgood's Potency and our Social Rejection; no relationship was found between our Dominance and Osgood's data.

Comparing our results with those of Valdez and Mehrabian (1994), we can see a full confirmation of the close correlation between Valence and Semantic Brightness (the positive emotional pole contains happiness, calm, and interest, and the brightest colors—white and sky-blue; the negative emotional pole contains anger, disgust, contempt, fear, and shame, and the darkest color—black). Our data on the close correlation between Arousal and Contrast Grey are similar to the data of Valdez and Mehrabian on Arousal and Saturation (Saturation is not represented as a separate axis in our four-dimensional model; it can be calculated only as the angle between the planes of hue and brightness). Figure 7 (right) demonstrates that Dominance, in addition to the transfer from white to green, also includes a local passage from white to grey and further to black. This coincides with the inverse relationship between Dominance and Brightness identified by Valdez and Mehrabian.

The analysis of Figs. 3–5 in Valdez and Mehrabian (1994), which reflect chromatic information, shows that the cluster of green, sky-blue, and blue, identified in Fig. 3 as the chromatic colors that have maximal positive estimates, fully coincides with our data. The plot correlating Arousal with Hue, given in Fig. 4, does not agree with our data; this may be attributed to statistically insignificant differences within Valdez and Mehrabian's data. A comparison of their Fig. 5, which reflects the relationship between Dominance and Hue, with our data shows the coincidence of the tendency toward green hues being closer to the pole of high Dominance.

The significant differences between our data and those of Valdez and Mehrabian are likely due to the different nature of the stimulation used in the studies. In our study, the color information was represented at the semantic level of representation, while they used the specific color charts of the Munsell system.

Analysis of four-dimensional emotional and color-emotional spherical models proposed in our study shows that these models can be treated as expansions of models suggested by Osgood (EPA), Mehrabian and Russell (PAD), and Russell (affective circumplex) and are substantially similar to the spherical models suggested by Sokolov.

The described axes of emotions have a complex neural basis. Possible brain mechanisms could be found in Sokolov and Boucsain (2000) and in Posner et al. (2005). In Sokolov and Boucsain (2000), specific balance of emotion-related neurotransmitters is believed to be the primary base of emotion. The information is gathered by two layers of subcortical "predetectors" (neuronal channels) and related basal ganglia emotional learning areas before it converges on cortical emotional detectors. For the predetectors that form Pleasure/Unpleasure (our Valence), the following areas are suggested: the lateral hypothalamus (1st layer), the anterior thalamic nucleus (2nd layer), and the nucleus accumbens at the emotional learning level. For Arousal/Dearousal, the reticular formation (1st layer) and the thalamic intralaminar nuclei (2nd layer) are suggested. For Dominance, similar to fear/anger as proposed by Sokolov and Boucsain, the ventral hypothalamus (1st layer), the medial thalamic nucleus (2nd layer), and the amygdala at the emotional learning level are suggested. Neural mechanisms for two emotional axes forming the affective circumplex suggested in Posner et al. (2005) substantially overlap the aforementioned data. For Valence, the mesolimbic dopamine system and asymmetry in frontal activation are suggested, and for Arousal, the reticular formation, the thalamic intralaminar nuclei, and the amygdala are suggested. In a more recent fMRI study (Posner et al., 2009), emotion-denoting words were used (similar to our approach) and the following areas were found to be related to Valence: the left insular cortex, the right dorsolateral prefrontal and precuneus cortices; and those related to Arousal were the left parahippocampus, the dorsal anterior cingulate cortex, the left dorsolateral prefrontal cortex, and the dorsal cerebellum. The abnormality of neural mechanisms in these two axes was also studied in autism spectrum disorders (Tseng et al., 2016). The neural basis for Social Rejection may include the anterior insula (bilaterally), the left anterior cingulate cortex, and the left inferior orbito-frontal cortex (Cacioppo et al., 2013).

The data gathered in our psychophysical study represent four emotional axes that could have the aforementioned neural mechanisms. The existence of a complex inter-modal neural mechanism that integrates color into a wider framework of emotions on the semantic level could be proposed. Further neuroimaging studies are required to examine this mechanism. Our preliminary research indicates that the default mode network could serve as this mechanism (Kiselnikov et al., 2018; Kozlovskiy et al., 2018).

Conclusion

Our study has shown that the best-fitting models for color and emotional semantics and for the integral color-emotional semantic are the four-dimensional spherical models that support the universality of the spherical model proposed by E.N. Sokolov (2013). The original method developed in our study allowed us to successfully actualize and measure color–color, emotion–emotion, and color–emotion semantic connections in a uniform metric. We were able to describe how colors and emotions interact on the semantic level, with the help of generalizing mechanisms of categorization. The data clarify the fundamental mechanisms of intermodal interaction of color and emotion at the semantic level, and open perspectives for practical use of this knowledge in applied psychology, ergonomics, psychodiagnostics, clinical psychology, psychophysiology, and cognitive neuroscience.

Limitations

The first limitation is related to the set of stimuli that was used in our study; this set was not broad enough to represent the full diversity of emotions and colors at the semantic level. The second limitation is related to all participants being Russian-speaking, which limits the possibilities of generalization.

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