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Blue blood, red blood. How does the color of an emotional scene affect visual attention and pupil size?

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ABSTRACT

The function of color in the processing of emotional scenes is not entirely clear. While there are studies showing that color matters in terms of the capture of covert attention by emotional stimuli, the impact of color on fixation patterns, reflecting overt attention, is unresolved. Studies on the role of color in evoking emotional response have also produced mixed results. Here, we aimed to explore how image color and content influence pupillary response and the engagement of overt visual attention. In the first experiment, we examined the pupillary reaction to neutral images (intact and phase scrambled) in three color variants (natural, abnormal, and grayscale). In the second experiment, we investigated the pupillary changes and fixation pattern in response to images of different valence (neutral, positive, and negative), again in three color versions. The results showed that pupillary responses were influenced by both content and the color of the images. The pupillary response to phase-scrambled images did not differ between the color versions. Intact neutral and positive images, but not negative ones, evoked smaller pupil responses if they were presented in abnormal colors rather than natural ones. The initial capture of attention by emotional content depended on the color version, whereas holding of attention was affected solely by the emotional valence. Thus, color changes the physiological response to images, particularly low-arousing ones, and modulates the initial engagement of attention by image content.

1. Introduction

The role of color in the processing of emotional images is an area of active discussion. While some studies show no effect of color on emotional response (Bradley, Codispoti, Cuthbert, & Lang, 2001; Codispoti, Cesarei, & Ferrari, 2012; Junghöfer, Bradley, Elbert, & Lang, 2001), several other studies show that color modulates some aspects of emotional image processing, such as the capture of covert attention (Bekhtereva & Müller, 2017; Kuniecki, Pilarczyk, & Wichary, 2015), brain responses to stimulus valence (Cano, Class, & Polich, 2009), and subjective evaluation of the emotional content of an image (Codispoti et al., 2012; Bekhtereva & Müller, 2017; Lu et al., 2015). Moreover, research on visual perception demonstrates that the processing of natural images, particularly object and scene recognition, benefits from color information (e.g., Gegenfurtner & Rieger, 2000; Hansen & Gegenfurtner, 2009; for review see Bramão, Reis, Petersson, & Faísca, 2011). Here, we examined whether color affects physiological reaction and the engagement of visual attention within natural scenes, both neutral and emotional. In particular, we examined whether emotional images in atypical colors and lacking color evoke the same pupillary response and pattern of fixations as images in natural colors. Hence in our analysis we focus on the interaction between emotional valence and the color version of an image.

Color is an important physical feature that supports the processing of natural images (for review see Gegenfurtner, 2003). In particular, Hansen and Gegenfurtner (2009) proved that color information serves as an important cue in object segmentation in images depicting natural scenes. Image coloring also helps in rapid categorization and recognition of natural scenes and objects (Gegenfurtner & Rieger, 2000), especially if a color is diagnostic for a given category (Goffaux et al., 2005; Oliva & Schyns, 2000; Tanaka & Presnell, 1999). Importantly, disruption of color information, either by adding colored noise or changing diagnostic colors, leads to a decrease in the efficiency of stimuli recognition (Oliva & Schyns, 2000; Tanaka & Presnell, 1999), an effect shown to be persistent in both humans and macaques (Liebe, Fischer, Logothetis, & Rainer, 2009).

Although research shows that color information aids scene segmentation and recognition, the role of color in guiding overt attention within a scene is still controversial. Most computational models of the allocation of visual attention take color into account as a predictive

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factor (Borji & Itti, 2013), but eye-tracking studies with natural images have not provided consistent evidence for the significant role of color in directing eye fixations. Analysis of the regions of natural images that engage visual attention has indicated that color plays a minor role in attracting fixations (Tatler, Baddeley, & Gilchrist, 2005). Also, abnormal coloring seems to only slightly affect visual exploration of images, shortening average saccade amplitudes in comparison to saccades on images in natural colors and grayscale (Ho-phuoc, Guyader, Landragin, & Guerin-Dugue, 2012). In particular, the authors did not find any differences in the location of fixations between images in natural colors, abnormal colors, or grayscale. Frey, Honey, and König (2008), however, argue that the role of color in directing fixations strongly depends on the content category of an image, hence averaging over various categories might yield insignificant results.

We argue that emotional images constitute a category in which color might be a particularly relevant feature. There is evidence indicating a link between colors and emotions, such as consistent emotional associations related to particular colors and inter-individual stability in color preferences (Kaya & Epps, 2004, Moller, Elliot, & Maier, 2009, Ou, Luo, Woodcock, & Wright, 2004; Taylor & Franklin, 2012). These associations might have evolutionary bases that link some colors to desirable objects that facilitate survival, such as fresh food or clean water, and others to unwelcomed objects posing danger, such as rotting food, contaminated water or feces (Palmer & Schloss, 2010). The proposition that color is particularly important in the emotional context seems to be supported by a previous study conducted by our team which showed that the color red preferentially engages attention but only in the context of emotional, not neutral, images (Kuniecki et al., 2015). Similarly, in an EEG study, Bekhtereva and Müller (2017) showed that color modulates the processing of emotional images. Emotional pictorial distractors presented in color attracted attention more than the same pictorial distractors presented in black and white, as indicated by the reduction of the *steady-state visual evoked potential* (SSVEP) response related to the main task. Moreover, the difference of evoked potentials related to the presentation of neutral and emotional images in the N1-EPN time window (170–400 ms after the stimulus) was larger when the images were presented in color than in grayscale. Taken together, these results show that particular hues, as well as color as a global feature of an image, can modulate the engagement of attention, especially in the emotional context.

The effect of color on other aspects of emotional processing, such as the physiological response to emotional stimuli, is an area of active controversy. Bradley et al. (2001) argue that the emotional response should be independent of color because emotional response is linked to the semantic content of an image, which remains unchanged after transformation of a color image into grayscale. Their findings seem in line with this prediction as they show that emotional images in grayscale evoke the same physiological reactions as colored pictures, regardless of their valence (positive, negative, neutral). Following studies using various EEG measures seem to confirm this line of reasoning by showing that both color and grayscale versions of emotional images trigger the same event related potentials (Codispoti et al., 2012; Junghöfer et al., 2001). However, a study by Cano et al. (2009) showed that P300 event-related potential is modulated by valence only when emotional images are presented in color. However, Bradley et al. (2001) pointed out that in the case of some images, such as those depicting blood, color may be important because it increases the similarity of an image to the real object.

Furthermore, the role of color in the subjective evaluation of the valence and arousal of emotional images also remains unresolved. Some studies provide evidence that color, as a global feature of an image, affects the evaluation of emotional images, especially those of negative valence. Specifically, negative colorful images are rated as more unpleasant and more arousing than the same images presented in grayscale (Bekhtereva & Müller, 2017; Codispoti et al., 2012). Lu et al. (2015) showed that subjects evaluate fear-inducing images higher on a fearfulness scale when they are presented in natural colors as compared to their grayscale versions. However, differences related to color were not detected by Bradley et al. (2001), who reported that valence ratings were the same for images presented in color or in grayscale.

Moreover, it is worth noting that in many studies regarding the role of color in image processing, researchers use grayscale images as a control condition (e.g., Bradley et al., 2001; Cano et al., 2009; Codispoti et al., 2012; Junghöfer et al., 2001). It can be argued that the complete removal of chromatic information is not synonymous with systematic manipulation of color. For this reason, in our study we decided to compare images in natural colors not only with images in grayscale, but also with images in transformed colors, using a transformation similar to that used by Ho-phuoc et al. (2012) and Oliva and Schyns (2000).

The aim of the present study was to examine the role of color in two aspects of emotional image processing: evoking physiological response and engaging visual attention. These two aspects are closely related in this context. On the one hand, the key semantic regions of emotional images preferentially attract attention (Humphrey, Underwood, & Lambert, 2012; Niu, Todd, & Anderson, 2012; Pilarczyk & Kuniecki, 2014). On the other hand, arousal indexed by a central physiological correlate such as late positive potential (Cuthbert, Schupp, Bradley, Birbaumer, & Lang, 2000) is enhanced when viewers' attention is cued directly towards the key region of an emotional image and reduced when cued away from it (Dunning & Hajcak, 2009; Hajcak, MacNamara, Foti, Ferri, & Keil, 2013). Together those two lines of evidence show that attention and arousal are mutually intertwined and hence should be jointly investigated when studying the perception of emotional images.

In the main study we presented negative, neutral, and positive images in natural colors, in abnormal colors, and in grayscale. To ensure that color manipulation was successful and to choose the most adequate images, the naturalness of the color before and after the transformation was assessed in a separate study. To the best of our knowledge, this is the first study to investigate the impact of color alternation on the pattern of fixations on emotional natural scenes. Furthermore, to our knowledge this is the first study which explores pupillary response to natural scenes, both neutral and emotional, in different color variants.

We expected that emotional images in natural colors, compared to images in abnormal colors, would evoke a stronger autonomic system response, measured as pupil size (Bradley, Miccoli, Escrig, & Lang, 2008; Bradley, Sapigao, & Lang, 2017). Secondly, we expected that the key objects in images in natural colors would engage attention more efficiently than the same objects in images in abnormal colors or in grayscale, especially in the case of emotional images. In addition, we carried out a control experiment in which we examined pupillary changes in response to neutral images in their intact and phase-scrambled forms, all presented in abnormal and natural colors, and in grayscale. The purpose of this control study was to determine whether pupil size was sensitive to color modifications per se, in which case the pattern of pupillary responses to different color versions would be the same for both intact and phase-scrambled images. Alternatively, if pupillary responses were influenced by the congruence between colors and the meaning of the depicted content, the color versions would modulate pupil size differently in the case of intact and phase-scrambled images.

2. Method

2.1. Participants

A total of 51 people (38 women) aged 19–42 ($M = 22.6$, $SD = 3.74$) participated in the evaluation of the naturalness of the images before and after the color transformations. Thirty-six people (26 women) aged 19–31 ($M = 23.3$, $SD = 3.46$) participated in the control study. Sixty-three subjects (45 women) aged 19–37 years participated in the main study (M = 23.1, SD = 3.42). In the main study, nine people were excluded from later analysis of eye movements and pupil size because the obtained calibrations were not precise enough (average calibration accuracy over 1°). Additionally, two people were excluded from pupil size analysis in the main study and one in the control study due to large pupil size data loss (over 50%). All subjects declared normal or corrected to normal visual acuity and normal color vision, and a lack of history of neurological diseases and anxiety disorders, in particular simple phobias. All participants signed an informed consent before each study in compliance with local ethics committee guidelines and the Declaration of Helsinki.

2.2. Materials

In the first step, we selected 240 images (80 negative, 80 neutral, and 80 positive) from databases of emotional images such as the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008), the Nencki Affective Picture System (NAPS; Marchewka, Żurawski, Jednoróg, & Grabowska, 2013), EmoPics (Wessa et al., 2010), the Geneva Affective Picture Database (GAPED; Dan-Glauser & Scherer, 2011), and from the internet. The inclusion of internet images was dictated by the insufficient selection of natural scenes in the published databases which met our criteria, as described below. Mean brightness and contrast of each image, calculated as the mean and standard deviation of the L* component in the L*, a*, b* color space were adjusted to constant values (110 for brightness and 60 for contrast) using Adobe Photoshop. Then, to create the abnormally colored versions, each image was transformed in the color domain by inverting the a* and b* values in the CIE 1976 color space L^*, a^*, b^* (similarly to Oliva & Schyns, 2000) using MATLAB (The MathWorks, Natick, MA, USA; Figs. 1 and 2). Grayscale versions of the images were created by leaving only information from the L^* channel, which represents the luminance of the image. In the second step, on the basis of the evaluation of color naturalness (see Section 2.3.), we selected a subset of 56 neutral images for the control study (Fig. 1) and 180 positive (e.g. children, landscapes, pets), negative (e.g. mutilations, accidents, dangerous animals), and neutral images (e.g. plants, food, farm animals) for the main study (Fig. 2). In addition, phase-scrambled (pink noise) versions of the images were generated for each color version of each of the 56 neutral images used in the control study (Fig. 1). Pink noise is obtained by replacing the phase in the Fourier spectrum of an original image with random values between 0 and 2 pi while preserving the amplitudes (Kayser, Nielsen, & Logothetis, 2006). The inverse Fourier transform with random phase and original amplitude values yields a pink noise image that keeps some of the original image characteristics, especially color, but all discriminable semantic information is lost.

In the main experiment, to study how visual attention is affected by the color version and valence of an image, we assessed the proportion of fixations directed at selected regions of interest (ROIs) and compared them between experimental conditions (see Section 2.4). The ROIs were defined as the key objects, i.e., the most meaningful and emotionally relevant regions within an image. The ROIs were determined in a procedure conducted prior to the control and main experiments (see Section 2.3). In this procedure, a separate group of participants was asked to mark key locations determining the valence of each image. For this task, we created a dedicated computer tool using custom JavaScript code. The participants were instructed to encircle, using the computer mouse, at least one region on each picture. Both the size and shape of the selections were unrestricted; however, the participants were asked to use simple shapes not to mark the entire scene but to focus on the key elements of the image. Then, the selections were averaged and a threshold was applied (a region encircled by at least 50% of the participants) to obtain key objects, which became the regions of interest (ROIs) for further analysis (Fig. 3). A total of 602 images were rated in this procedure by 241 participants. Each participant rated 60–80 images, each of which was rated on average by 27 participants (SD = 4.04). Fig. 3 presents the original picture, the averaged participants' selections of the key object, as well as the final region of interest.

The set of images presented in the main study was chosen to avoid any differences in the naturalness ratings between valence conditions, within both the natural and abnormal color conditions. The images also did not differ in terms of the mean area of the region of interest, calculated as a percent of the total image area in pixels. The naturalness ratings, the ROIs' areas, as well as the valence and arousal ratings for each emotional category together with the results of ANOVA tests are

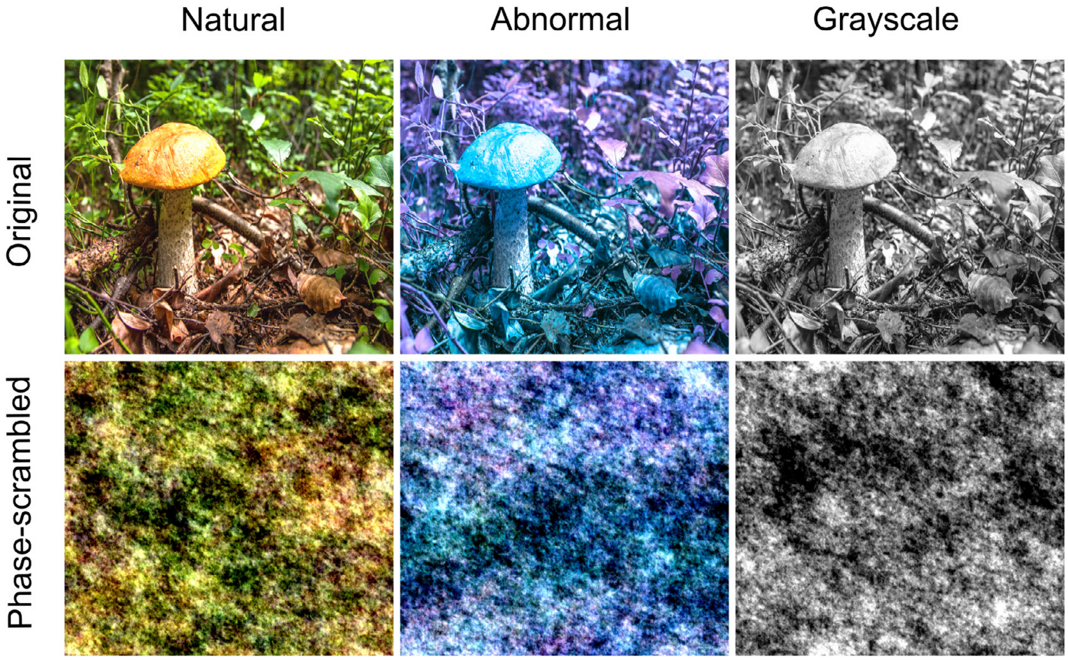

Fig. 1. Examples of the original, intact images and their phase-scrambled (pink noise) versions, presented in natural colors, abnormal colors, and in grayscale, analogous to the ones used in the study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Examples of the negative, neutral, and positive images used in the study, or similar ones, in natural colors, abnormal colors, and grayscale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

presented in Table 1. Valence and arousal ratings differed between all emotional categories ($p < .001$), as evidenced by pairwise comparisons analysis. The valence and arousal evaluations were obtained from the databases' normative ratings. In the case of the images taken from the internet, the ratings were obtained in a separate procedure using the Self-Assessment Manikin scale (Bradley & Lang, 1994). Each image was evaluated on average by 29 participants ($SD = 4.16$).

Color naturalness was evaluated on a scale 1 (completely unnatural) to 9 (completely natural). Emotional evaluation presents ratings on a 1–9 scale, negative to positive for valence and low to high for arousal. The ROI is calculated as a percent of the total image area, i.e., the number of pixels in a ROI divided by the total number of pixels in the image.

2.3. Procedures

In all experiments, we used PsychoPy software (Peirce, 2007) to control stimuli presentation and response collection. In all procedures

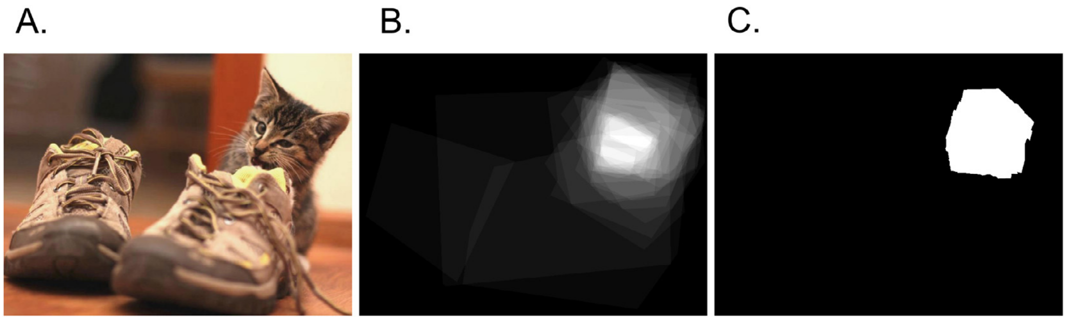

Fig. 3. Example of (A) an original image, (B) averaged selections of the key object, and (C) region of interest (ROI).

Table 1
Statistics of the images used in the main experiment, together with the results of ANOVA tests.

Image category	Color naturalness		Emotional evaluation		ROI
	Natural	Abnormal	Valence	Arousal	ROI area (%)
Negative	7.65	1.74	2.72	6.32	10.79
Neutral	7.82	1.72	5.60	3.83	11.97
Positive	7.73	1.70	7.20	4.50	11.42
$F(2,177)$	.74	.10	605.83	152.07	.49
p-value	.48	.91	< .001	< .001	.61

the order of image presentation was randomly chosen for each participant. The randomization was controlled by PsychoPy. There were no additional restrictions with respect to the order of the image presentation. Images were displayed on monitors calibrated using the X-Rite ColorMunki colorimeter to white point D65 and luminance 120 cd/m^2, in a room with constant artificial lighting set to 70 lux. The participants were seated approximately 75 cm from the computer screen. In the control and the main studies, eye movements and pupil size were measured using the Mirametrix S2 eye tracker (Montreal, Canada) at 60 Hz.

2.3.1. Evaluation of the naturalness of image colors

The participants were asked to assess the naturalness of the colors of presented images, i.e., the extent to which they reflected the real-world coloring of objects and scenes. For the assessment, we used a scale from 1 (completely unnatural) to 9 (completely natural). Each participant evaluated all 240 images in random order, but each of the images was evaluated by the participant in only one, randomly selected, color version (natural or abnormal). Images in each color version were rated on average by 25 people (aged 16–35; $SD = 3.5$). The time for the evaluation of the images was unlimited, but on average the session lasted 30 min.

2.3.2. Control study procedure

In the control study, 56 original images and 56 phase-scrambled images were presented in a free-viewing procedure. Each participant viewed each original image and each phase-scrambled image in only one randomly selected color version: natural, abnormal, or grayscale. The study was divided into eight 4-minute blocks, starting with the calibration of the eye tracker. If necessary, the calibration of the eye tracker was repeated until an average accuracy of less than 1° of visual angle was achieved. Fourteen images were presented in each block. Presentation of each image (6–8 s, randomly) was preceded by a centrally located fixation point (9–12 s, randomly).

2.3.3. Main study procedure.

One hundred and eighty images were presented in a free-viewing procedure. Each subject viewed each image in only one, randomly selected, color version: natural, abnormal, or grayscale. The study was divided into ten blocks, each lasting approximately 6 min, starting with the calibration of the eye tracker. If necessary, the calibration of the eye tracker was repeated until an average accuracy of less than 1° of visual angle was achieved. Sixteen images were presented in each block. The presentation of each picture (5–6 s, randomly) was preceded by a centrally located fixation point (9–12 s, randomly).

2.4. Data analysis

Pupil size and eye-tracking data preprocessing were conducted using MATLAB (The MathWorks, Natick, MA, USA). Pupil size data was resampled, filtered, and interpolated using MATLAB toolbox provided by Kret and Sjak-Shie (2018) with default settings. First, using the toolbox we filtered the raw signal to remove invalid data samples with default dilation speed filters, filters detecting temporally isolated samples, and filters detecting outliers from the trend line. The signal was then resampled with interpolation to 1000 Hz and smoothed using a low-pass filter with default toolbox settings. The sections that would be interpolated over gaps larger than 250 ms were treated as missing. For more details regarding the filter settings, please see Kret and Sjak-Shie (2018). Trials with more than 25% pupil size data loss were treated as invalid and were excluded from the statistical analysis. After excluding participants with large pupil data loss (over 50% of all trials), only 0.6% of trials in the main and 0.6% trials in the control study were not valid. All remaining participants had over 95% of valid trials in the main experiment and over 93% in the control experiment. Statistical analysis was performed using SPSS (SPSS, Inc., Chicago, Illinois, USA).

2.4.1. Control study

After the preprocessing of the pupil size data, fragments lasting from 1 s before the stimulus onset (baseline level) up to 4 s after its onset (phasic reaction) were extracted from the continuous recording. Data were normalized separately for each trial by subtracting from each data point the average of the one-second period preceding the stimulus presentation. Subsequently, a repeated measures ANOVA was carried out with the following factors: presence of noise (original images, phase-scrambled images) and color version (natural, abnormal, grayscale). The analysis was conducted on normalized data, averaged within a time window of 1.5–4 s after stimulus onset. For statistics and data presentation, pupil diameter in pixels was converted to mm using a pixel-to-mm conversion factor, which was derived from the eye tracker given the subject to tracker distance.

2.4.2. Main study

The pupil size data preprocessing and normalization was conducted in the same manner as in the control study. Saccades were detected using the default algorithm of the Mirametrix S2 eye tracker. Fixations were defined as periods between saccadic eye movements, excluding blinks. Although we did not set a duration threshold to eliminate microfixations, fixations longer than 100 ms comprised over 98% of the analyzed data. Allocation of visual attention was assessed using normalized versions of three indices: the first fixation proportion (FFP), the first pass duration (FPD), and the total dwell time (TDT). FFP reflects the proportion of the first two fixations on an image that fell in the region of interest (ROI), i.e., the key object within a scene (see Section 2.2), to those that were outside this area. The FPD is an index of the total duration of successive fixations made during the first engagement of attention by the ROI. The TDT is defined as the cumulative fixation duration within the ROI throughout the whole stimulus presentation period. The three indices were normalized, as described for the first time in Pilarczyk and Kuniecki (2014), to compensate for both the size of the ROI and the tendency to scan central areas of an image more frequently than its peripheries. In order to obtain the normalized FFP (nFFP), first we computed the fraction of the first two fixations in an image that fall within an ROI while looking at the analyzed image (positive sample). Second, we computed the fraction of the first two fixations that were made in the same location as the ROI by the same person while watching different images belonging to the same valence and color category (negative sample). Thus, the size of the negative sample indicates a general tendency to make two initial fixations at this particular location of a scene, regardless of its content. For each image category and each person, the percent values of the positive sample were divided by the percent values of the negative sample, giving the normalized FFP (nFFP). The indices based on fixation durations, i.e. the normalized FPD (nFPD) and normalized TDT (nTDT), were calculated in an analogous manner. In effect, if a normalized index equals one, then the fixation proportion or duration can be explained solely by the ROI's size and location. For instance, if the nFFP equals one, the chance of directing two initial fixations at the ROI of the analyzed image is equal to the chance of directing them at the same region while also viewing other pictures, e.g., due to the central location of this region or

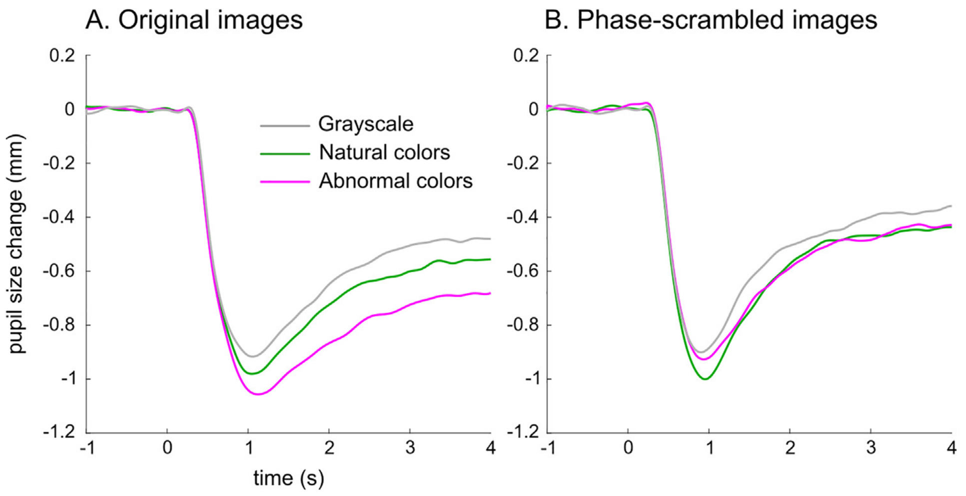

Fig. 4. Mean pupil diameter change in millimeters during baseline and the first four seconds of image presentation for (A) original and (B) phase-scrambled images in natural colors, abnormal colors, and grayscale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

its large size. If an index is larger than one, this indicates how many times the proportion of fixations is larger than expected by chance or how many times the cumulative fixations duration is longer than expected by chance. If it is smaller than one, this shows how many times it is smaller or shorter than is expected by chance.

Next, repeated measures analyzes of variance (rmANOVA) with factors of valence (negative, neutral, positive) and color version (natural, abnormal, grayscale) were carried out on both the pupil diameter change and each fixation index (nFFP, nFPD, nTDT).

3. Results

3.1. Control experiment

The relative pupil size (Fig. 4) averaged in the 1.5–4 s time window depended on the color version condition (F(2,68) = 15.81, p < .001; partial η2 = 0.32), the presence of noise (F(1,34) = 45.30, p < .001; partial η2 = 0.57) and the interaction of these factors (F (2,68) = 12.70, p < .001; partial η2 = 0.27). In the case of original images, pupil size was smaller in response to images in abnormal colors than to images in natural colors (p = .002) and grayscale (p < .001). The difference between the images in natural colors and the grayscale images was also significant (p = .027), with larger pupil size in response to the latter. In the case of phase-scrambled images, only one difference proved to be significant: the pupil was smaller in response to images in natural colors than to images in grayscale (p = .036).

3.2. Main experiment

The relative pupil size averaged in the 1.5–4 s time window was affected by valence (F(2,102) = 33.35, p < .001; partial η2 = 0.40; Fig. 5). The pupil was largest in the negative condition and did not differ between neutral and positive conditions. This pattern of results was observed in all color versions (Fig. 6). The effect of color version on pupil size was also significant (F(2,102) = 39.00, p < .001; partial η2 = 0.43 Fig. 5). All pairwise comparisons yielded significant differences. Pupil size was the smallest for abnormal colors, largest for grayscale images, and its size was intermediate size in the case of natural images. Importantly, the color condition interacted with valence (F(4,204) = 2.66, p = .034; partial η2 = 0.05; Fig. 5). The pattern of results observed in the main effect of color version was present only for positive and neutral images (p < .05). In the negative condition, the pupil was larger in response to grayscale images than to images in natural (p < .001) and abnormal colors (p < .001), while there was no difference between the natural and abnormal color conditions (p = 1).

The normalized first fixation proportion (nFFP) in the ROI did not significantly differ with respect to the color version (*F*(2,106) = 0.59, *p* = .56; partial η2 = 0.01) and the image valence (*F*(2,106) = 3.14, *p* = .058; partial η2 = 0.06). However, the interaction of these factors reached statistical significance (*F*(4,212) = 2.60, *p* = .037; partial η2 = 0.05; Fig. 7). A pairwise comparisons analysis showed only one significant difference between positive and negative images in the natural colors condition (*p* = .001; Fig. 7), with larger nFFP in the negative condition. However, there were no significant differences in the nFFP between color versions within each emotional condition.

The normalized first-pass duration (nFPD) was modulated by the valence (*F*(2,106) = 13.55, *p* < .001; partial η2 = 0.2; Fig. 8A) but not by the color version of an image (*F*(2,106) = 1.32, *p* = .27; partial η2 = 0.02) or the interaction between valence and color version (*F* (4.212) = 1.38, *p* = .24; partial η2 = 0.03). Also, the normalized total dwell time (nTDT) was influenced only by the valence (*F* (2,106) = 18.86, *p* < .001; partial η2 = .26; Fig. 8B), but not by the color version of an image (*F*(2,106) = .11, *p* = 0.89; partial η2 = .002) or the interaction between valence and color version (*F*(4,212) = 0.61, *p* = .65; partial η2 = .01).

4. Discussion

The aim of our study was to determine whether the colors of an emotional image influence the engagement of visual attention and whether it modulates the physiological reaction to the image presentation. In the two experiments, we presented neutral and emotional images in natural, abnormal, and grayscale color versions while recording fixation patterns and pupil diameter.

4.1. The effects of meaning and color on pupillary changes

In the control study, we presented neutral images and their visual noise versions in all three color variants to check whether color transformations *per se* affect pupil size. It is particularly interesting that the pupil size differed between natural and abnormal colors only if images depicted meaningful scenes, but not when they were devoid of any semantic content. In the case of meaningful scenes, pupil size was smaller in response to the presentation of images in abnormal colors than to those in natural colors and grayscale. In the case of phase-scrambled images, the difference between natural and grayscale versions was also significant, showing the same pattern as in the case of meaningful scenes. Abnormal color version, however, did not differ from any other. It is worth noting that the meaningless, phase-scrambled images preserved the overall coloring of the original images. Therefore, the results indicate that only the combination of meaningful

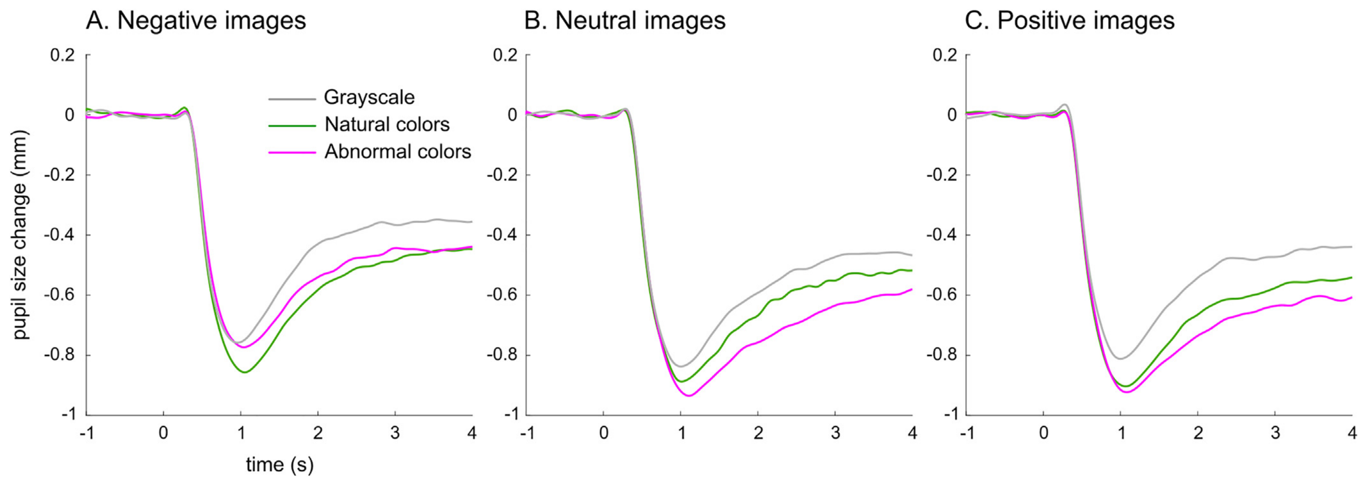

Fig. 5. Mean pupil diameter change in millimeters during baseline and the first four seconds after image onset for (A) negative, (B) neutral, and (C) positive images in natural colors, abnormal colors, and grayscale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

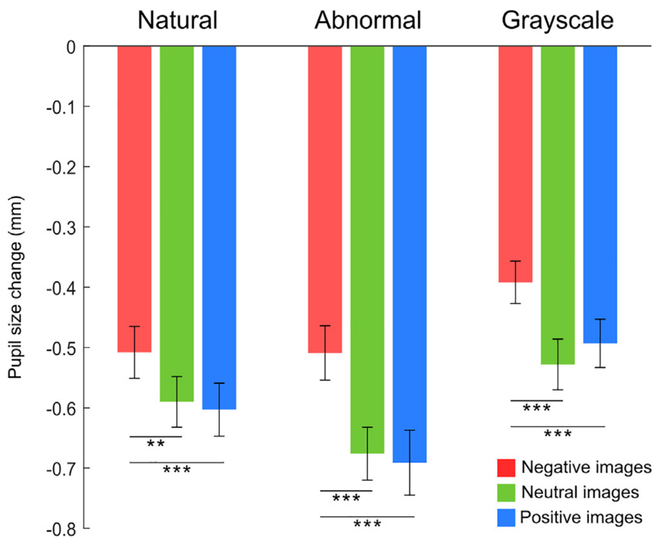

Fig. 6. Pupil diameter change in millimeters in the 1.5–4-second time window for all color types and valence conditions. Error bars indicate standard error. Statistically significant differences in pairwise comparisons are marked with *** at $p < .001$ and ** at $p < .01$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

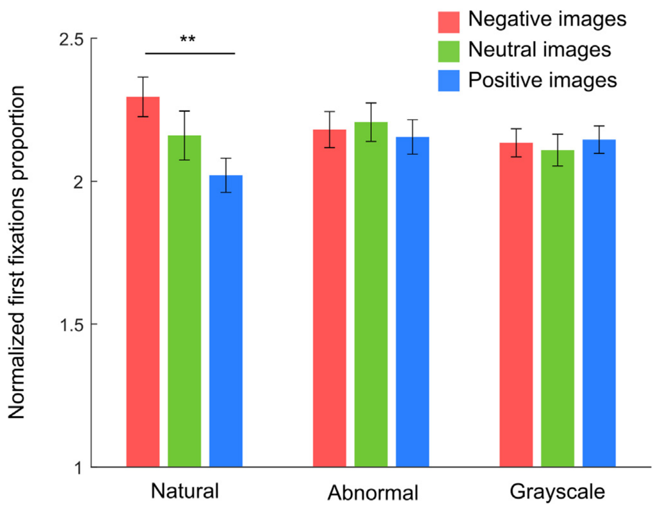

Fig. 7. Normalized first fixation proportion (nFFP) in the region of interest for negative, neutral, and positive images in natural colors, abnormal colors, and grayscale. Error bars represent standard error. Statistically significant difference in pairwise comparisons is marked with ** at $p < .01$. The value 1 on the y axis indicates the random level, i.e. the one at which the proportion of fixations in ROI can be explained solely by its size and location. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

content with abnormal colors induces the differentiation of pupil size.

The effect of color version on pupil change that was detected in the control experiment for meaningful images could hardly be attributed to the differences in the emotional response since all presented images were neutral in terms of their emotional valence. It seems more likely that this effect is related to the oddness of images in abnormal colors. The observed pupillary response might be analogous to the old/new effect described by Võ et al. (2008), who showed that the presentation of new verbal stimuli leads to smaller pupil dilation than in the case of familiar stimuli. This effect has been confirmed in later studies on memory processes using not only words (Brocher & Graf, 2016) but also objects (Kafkas & Montaldi, 2015) and natural images depicting neutral content (Naber, Frassle, Rutishauser, & Einhauser, 2013). Although all the images in our study were new to the participants and were presented only once during the experimental session, the images in abnormal colors are rated as less typical, as evidenced by our survey (see Table 1), and most likely they were less frequently encountered by the participants, thus making them less familiar. Importantly, Kafkas and Montaldi (2015) showed that the old/new effect cannot be explained by cognitive effort, since its increase causes pupil dilation and not constriction.

4.2. *The effects of valence and color on pupillary changes*

As expected, the results of the main study showed an interaction between the depicted content and the color version of an image. In the case of neutral and positive but not negative images, pupil size was smaller when images were presented in abnormal colors as compared to natural and grayscale versions. This pattern of results was similar to that obtained in the control experiment. It seems, therefore, that in the case of neutral as well as positive images, changes in pupil diameter evoked by presentation of stimuli in abnormal colors can also be attributed to the oddness of these images.

Interestingly, in the case of negative images there was no difference between images in natural and abnormal colors. One explanation for

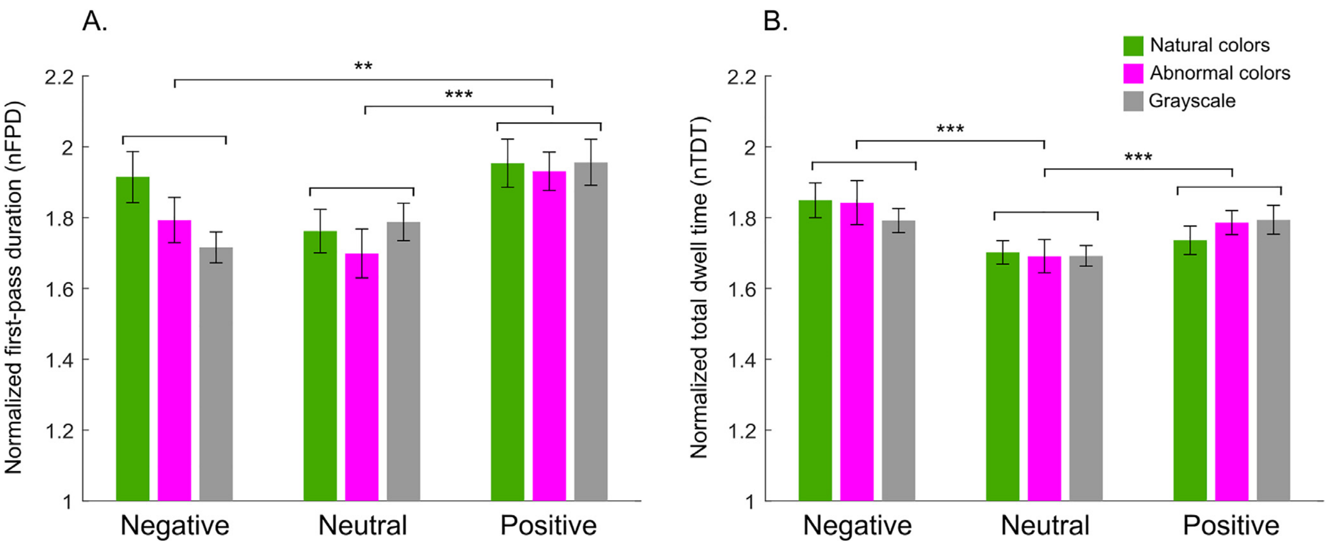

Fig. 8. (A) Normalized first-pass duration (nFPD) and (B) normalized total dwell time (nTDT) for negative, neutral, and positive images. Error bars indicate standard error. Statistically significant differences in pairwise comparisons between valence conditions (averaged across color conditions) are marked with *** at $p < .001$ and ** at $p < .01$. The value 1 on the y-axis indicates the random level at which an index can be solely explained by the ROI's size and location. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

this effect might be related to the general abnormality of negative images, regardless of their colors. While neutral and positive images mainly depict scenes from everyday life (e.g., common objects, landscapes, food, animals), the content of negative images (e.g., operations, corpses, mutilation) mainly includes less typical examples of the participants' daily experience. Moreover, as some authors have suggested (Acunzo & Henderson, 2011; Humphrey et al., 2012), emotional objects, in particular negative ones, are often atypical elements that contrast with the neutral context of a scene. We might speculate that in such a situation abnormal colors might be of secondary importance to the unusual content of pictures. Another explanation might involve the high arousal induced by negative pictures. Interestingly, an analogous result was obtained by Võ et al. (2008), who showed an interaction of novelty and emotional arousal: pupil dilation did not differ between new and old arousing words, both positive and negative, but only between new and old neutral words. A similar pattern of results was reported by Ferrari et al. (2016) using repeated and new emotional and neutral scenes. In sum, it seems that the effect of color oddness, as well as the old/new effect, might be inhibited in the case of arousing emotional stimuli. In our study, positive images, although also emotionally relevant, did not evoke pupillary responses similar to negative images. In fact, we did not observe differences in pupil size between neutral and positive images in any color condition (Fig. 6). This might be due to the lower mean arousal ratings of positive stimuli than negative ones.

Lastly, it is worth noting that the evaluation of the naturalness of the colors did not differ significantly between the valences of the images in both natural and abnormal color versions. Therefore, the interaction between valence and color in pupil size cannot be explained by the lack of balance in the experimental conditions in terms of the naturalness of colors.

4.3. *Pupillary changes in response to grayscale images*

In the case of grayscale images, we surprisingly detected larger pupillary responses as compared to images in other colors. This effect seems very robust as it was present in both the control and the main study as well as in all emotional conditions. A similar result was obtained by Kuzinas, Noiret, Bianchi, and Laurent (2016), who presented nature and urban scenes in original colors, in grayscale, and in two tinted versions of grayscale images (red and green). The authors observed larger pupil dilation in response to grayscale images in comparison to other color conditions, despite equal luminance of all the stimuli. In the light of the previous findings, it seems highly improbable that increased pupil size in response to grayscale images was due to particularly high emotional arousal induced by this type of image. In the study by Kuzinas et al. (2016), the increased pupil diameter in the grayscale condition did not correspond to the ratings of arousal, which were lower in the case of images in grayscale as compared to color images. In general, emotional images presented in grayscale are rated as evoking lower (Bekhtereva & Müller, 2017; Codispoti et al., 2012; Lu et al., 2015) or the same (Bradley et al., 2001) intensity of valence and arousal compared to images in original colors. The only exceptions are portraits, which are rated as more positive in grayscale than in the full range of colors (Polzella, Hammar, & Hinkle, 2005); however, portraits were not used in our study. In summary, we suppose that this phenomenon of grayscale stimuli causing larger pupillary change than chromatic stimuli might reflect some basic psychophysical effect which does not yet have a clearly described physiological interpretation.

Lastly, it is worth noting that presentations of images in abnormal colors and images in grayscale produced opposite pupillary effects in comparison to images in natural colors. This observation confirms the notion that the deletion of color information, which is often used in studies on the role of color, is not identical to color transformation. The opposite direction of these effects might also suggest that different mental processes are involved in the perception and recognition of images that lack color information and images that contain incongruous color information.

4.4. *Engagement of attention by valence and color*

The eye-tracking data shows an interaction between valence and color version. Namely, the proportion of the first two fixations directed at the region of interest, i.e., the key object in a scene, depended on the image valence, with a larger proportion of fixations falling in key objects in negative images and a smaller proportion in positive ones, but only when images were presented in their natural colors. However, if the colors were abnormal or if an image was presented in grayscale, valence did not influence the proportion of initial fixations falling into ROIs. It can, therefore, be hypothesized that early attention capture by key objects in images of negative valence that has been observed in earlier studies (Humphrey et al., 2012; Kuniecki, Wołoszyn, Domagalik, & Pilarczyk, 2017; Niu et al., 2012; Pilarczyk & Kuniecki, 2014) is partially aided by color.

The fact that the key objects in the positive images presented in natural colors attracted the smallest proportion of the first fixations might be surprising, especially since these objects were fixated for the longest time during the first-pass viewing. The total time of viewing key objects, however, did not differ between negative and positive ones. Therefore, in the case of the initial capture of attention on images in natural colors we observed the negativity bias (Fig. 7), followed by a positivity bias in the initial holding of attention (Fig. 8A), and a general emotionality effect during the entire image presentation (Fig. 8B). A similar effect, that is, a dissociation between the negativity and emotionality effects in the measures of capture and holding of attention by emotional objects, was also observed in a study by Humphrey et al. (2012).

The holding of attention by key objects remained unchanged despite color manipulations. Participants fixated the key objects for an equally long duration in all color versions of images, both during the first pass (nFPD index) and during the entire image presentation (nTDT index). The relatively small impact of color on fixation patterns corresponds with the results reported by Ho-phuoc et al. (2012), who showed that there are no differences in fixation locations resulting from color manipulation. However, the authors reported longer fixation durations in the grayscale condition, while in our study measures related to fixation time, i.e., total dwell time and first-pass duration, were unaffected by color version. It is worth noting that the color transformations used in our study altered image colors more significantly than those used by Ho-phuoc et al. (2012), in which, for example, the green color remained almost intact. Hence, it seems that even a dramatic change in the naturalness of colors does not affect the later stages of visual exploration of images, which demonstrates the robustness of the perceptual system. This coincides with our earlier findings, which showed that directing attention at the key object of an image is effective even at very low signal-to-noise ratios (Pilarczyk & Kuniecki, 2014). The robustness of the holding of attention but not the capture of attention measures to color manipulation also corresponds with results reported by Nummenmaa, Hyönä, and Calvo (2010), who showed that recognition of the semantic content of an image occurs extremely quickly and constitutes a basis for the identification of emotional valence. It seems plausible that the content of images in natural coloring was decoded more quickly than in the case of images in abnormal colors and grayscale, as natural coloring aids scene segmentation and identification (for review see Gegenfurtner, 2003). This might have led to the differences between color conditions that were observed in our study, i.e., a significant effect of valence at the early stage of attention deployment for images presented in natural colors but not images in abnormal colors and grayscale. At the later stages of stimulus perception, spatial attention depended primarily on the emotional valence of the presented image, while its color did not influence the dynamics of attention allocation.

We might speculate that the seemingly effortless adaptation of the visual system to abnormal image coloring could be related to the phenomenon of color constancy (for reviews see Foster, 2011; Werner, 2014), i.e., subjective perception of objects' colors as relatively constant despite the changing intensity and spectrum lighting. The phenomenon of color constancy shows that the perceptual system adapts very easily to different lighting conditions and thus altered colors of a scene. Since in our study the entire color spectrum of a scene was shifted, the relative differences between colors were preserved. Therefore, it is possible that in our study a phenomenon occurred that is somewhat similar to color constancy and which led to the lack of significant differences in the distribution of fixations due to the color after the initial stage of image exploration. This hypothesis could be verified in a study comparing the perception of images in which all colors were subjected to a linear transformation, analogously to our study, with images in which only the color of the key object was modified. It is also possible that visual attention is sensitive to specific hues, not colors in general. For instance, it has been shown that red particularly affects spatial attention (Fortier-Gauthier, Dell'acqua, & Jolicoeur, 2013; McMenamin et al., 2013), especially in the emotional context (Kuniecki et al., 2015). Hence, maybe more targeted color transformation, e.g., only of reddish hues, would be of interest in further studies.

5. Conclusions

In summary, our results indicate that image processing is modulated by an interaction between the color and content of an image. The most striking difference in the pupillary response was observed between meaningful neutral scenes and their non-meaningful, phase-scrambled versions. The phase-scrambled images evoked the same pupil changes regardless of color transformation, while the pupillary response to meaningful real-world images was significantly affected by the abnormality of the color. Hence, out of the two predictions we intended to test here, we can refute the one which assumes the uniform influence of color on pupillary response irrespective of image meaning, and we can accept the alternative premise that the pupil reacts to the congruence of color and content, rather than to color on its own. This effect is further modulated by emotional content. Neutral and positive images in abnormal colors evoked smaller pupillary response than those in natural colors, which might be related to the oddness of abnormally colored images. In the case of negative images, this effect disappeared. Possibly, in the case of negative images, the effect of emotional arousal or content abnormality interferes with the effect of color abnormality. Surprisingly, grayscale images evoked the largest pupillary response in all tested conditions. Overall, the results did not support our hypothesis that in the case of emotional images the color version is more important than in the case of neutral images. On the contrary, it seems that if the emotional content of an image is highly arousing, the color is of minor importance, whereas the processing of low-arousing images is significantly affected by the congruence of color and content.

The color version of an image also played a modulatory role in the initial capture of attention by emotional objects. The emotional valence of a scene affected the capture of attention only if images were presented in natural colors, but not in abnormal colors or grayscale. At the later stages of the visual exploration of a scene, visual attention functioned similarly regardless of whether the color was typical for an image or whether color information was present at all. Hence, our hypothesis predicting that objects in natural colors would engage attention more efficiently was not entirely confirmed. In fact, our results provide evidence that even severe alteration of the color of an image does not affect the holding of attention, whereas the initial capture of attention by emotional content might be modulated by color information.

CRediT authorship contribution statement

Joanna Pilarczyk: Conceptualization, Methodology, Software, Resources, Writing - original draft, Visualization, Project administration. **Michał Kuniecki:** Methodology, Software, Formal analysis, Resources, Writing - review & editing, Supervision, Funding acquisition. **Kinga Wołoszyn:** Resources, Investigation, Writing - review & editing. **Radosław Sterna:** Investigation, Writing - original draft.

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neutral image presented in Figs. 1 and 2 was downloaded under the Pixabay License: author, Pawel Litwin; source, https://pixabay.com/en/mushrooms-kozak-mushroom-forest-2715993/ (cropped, transformed colors).

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