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High entropy of edge orientations characterizes visual artworks from diverse cultural backgrounds

Christoph Redies [a,b,*], Anselm Brachmann [a], Johan Wagemans [b]

[a] Experimental Aesthetics Group, Institute of Anatomy I, University of Jena School of Medicine, Jena University Hospital, D-07740 Jena, Germany
[b] Laboratory of Experimental Psychology, Brain & Cognition, University of Leuven (KU Leuven), Tiensestraat 102, B-3000 Leuven, Belgium

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ABSTRACT

We asked whether "good composition" or "visual rightness" of artworks manifest themselves in a particular arrangement of basic image features, such as oriented luminance edges. Specifically, we analysed the layout of edge orientations in images from a collection of >1600 paintings of Western provenance by comparing pairwise the orientation of each edge in an image with the orientations of all other edges in the same image. From the resulting orientation histograms, we calculated Shannon entropy and parallelism (i.e., the degree to which lines are parallel in the image). For comparison, we analysed the same second-order image properties in photographs of diverse natural patterns and man-made objects and scenes. Results showed that Shannon entropy of relative orientations of edge pairs was high and parallelism was low for the paintings and some of the natural patterns, but differed from other sets of photographs, including other man-made stimuli. The differences were also observed when images were matched for image content. Moreover, high entropy of edge orientations was found in traditional artworks produced by different techniques, in artworks that represented different content matter and art genres, as well as in artworks from other cultural backgrounds (East Asian and Islamic). In conclusion, we found that high entropy of edge orientations characterizes diverse sets of traditional artworks from various cultural backgrounds.

1. Introduction

At early stages of cortical processing, visual information is encoded locally by an array of retinotopic filters distributed over the visual field. For example, groups of neurons in the primary visual cortex (V1) respond to luminance edges of a particular orientation projected onto their receptive field (orientation columns) (Wurtz & Kandel, 2000). The V1 responses are influenced also by large-scale interactions that extend well beyond the classic receptive field (Field, Hayes, & Hess, 1993) and contribute to the sparse coding and decorrelation of visual responses (Simoncelli & Olshausen, 2001), e.g. by surround modulation, horizontal long-distance connections, and top-down influences from higher-order areas (Spillmann, Dresp-Langley, & Tseng, 2015). Both local processing and long-distance interactions are adapted in evolution and development to the statistics of the natural environment (Coppola, Purves, McCoy, & Purves, 1998; Geisler, 2008). They have evolved for specific perceptual tasks, for instance, for the recognition of objects by detecting border-ownership relations or for the rapid recognition of scenes by integrating information across a wider region of the visual field.

While a vast body of knowledge about the role of local feature extraction in visual perception has been gathered, we are just beginning to understand how specific perceptual tasks are mediated by the integration of visual information across the visual field. One striking example of our lack of knowledge is the perception of "visual rightness" and "good Gestalt" in visual artworks (Arnheim, 1954; Locher, Stappers, & Overbeeke, 1999). Some artists, art historians and art critics have argued that the structure of artworks follows specific, as yet unknown rules of spatial composition (Bell, 1914; Greenberg, 1955; Kandinsky, 1912; Redies, 2015), which asks for an arrangement of pictorial elements in precise spatial relations to each other in an artwork. If this notion is correct, the perception of artworks must be reflected in long-range interactions of neuronal responses across the visual field. Although some contemporary philosophers, psychologists and art critics have contested such formalist views, especially for (post-)modern art (Danto, 1981; Gopnik, 2014; Leder, Belke, Oeberst, & Augustin,

* Corresponding author at: Institute of Anatomy I, Jena University Hospital, D-07740 Jena, Germany.
E-mail addresses: christoph.redies@med.uni-jena.de (C. Redies), anselm.brachmann@med.uni-jena.de (A. Brachmann), johan.wagemans@kuleuven.be (J. Wagemans).

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2004), several statistical image properties have been found to be associated with artworks in recent years (Graham & Redies, 2010). For example, there is converging evidence that, in general, observers prefer an intermediate degree of visual complexity in visually pleasing stimuli, such as artworks (Forsythe, Nadal, Sheehy, Cela-Conde, & Sawey, 2011). Moreover, large subsets of artworks resemble complex natural scenes in that they possess a scale-invariant Fourier spectrum (Graham & Field, 2007; Redies, Hänisch, Blickhan, & Denzler, 2007). Also, the spatial distribution of oriented luminance gradients in many artworks is characterized by a relatively high degree of self-similarity and uniformity across directions (Braun, Amirshahi, Denzler, & Redies, 2013; Redies, Amirshahi, Koch, & Denzler, 2012). Despite these intriguing results, distinct perceptual features that discriminate artworks from more mundane examples of man-made images remain elusive to date.

Against this background, the present work aims to increase our knowledge about how the physical structure of traditional artworks differs from that of other visual stimuli (Bell, 1914; Graham & Redies, 2010) and to what extent their processing in the human brain can possibly be tied to objective stimulus parameters. Even if it turns out that the same stimulus features cannot be identified universally in all artworks, especially in some examples of (post-)modern and contemporary art (Danto, 1981; Gopnik, 2014; Leder et al., 2004), our approach may lead to a classification of different types of artworks according to objective image properties, before considering the role of content, cultural context, personality, expertise and the like in art appreciation (Leder et al., 2004; Redies, 2015).

Because the detection of oriented luminance gradients, such as edges, is a fundamental and early outcome of visual processing, one obvious experimental question is how edge orientations relate to each other in images of artworks. In other words: Do "visual rightness" and "good composition" (Arnheim, 1954; Bell, 1914; Locher et al., 1999) manifest themselves in a particular arrangement of oriented edges in images of traditional artworks? To answer this question, we used Gabor filters to determine the orientations of all edges in the images. The strongest edges were identified and the orientation of each of the edges was compared pairwise to the orientation of all other strong edges in the image. As expected, results provided evidence for prominent statistical regularities for nearby edge pairs (e.g., collinearity) as well as for more distant edge pairs (e.g., parallelism) (Geisler, Perry, Super, & Gallogly, 2001). Surprisingly, for more widely separated edge pairs, edge orientations showed a low degree of regularity in a large set of oil paintings of Western provenance, i.e. the edge orientations in these artworks were largely independent. This result implies that, across each image, artworks exhibit a high degree of second-order entropy of edge orientations. This high second-order entropy can be reduced only partially to the first-order entropy of edge orientations. For comparison, regularities of distant edge pair orientations were higher and, consequently, second-order entropy was lower for other types of man-made images and in visual stimuli that we encounter in every-day life (photographs of architecture, objects, and human faces). A similar difference between non-artistic and artistic images was found for images that displayed similar content (face photographs *versus* face portraits, and landscape photographs *versus* landscape drawings). Moreover, we studied whether high entropy of edge orientations is also observed in artworks that were produced by different artistic techniques (oil and ink paintings, graphic art and prints) and in other cultures (Islamic and East Asian art). Last but not least, we asked whether high entropy of edge orientations could also be found when we analyse colour-opponent channels of intensely coloured artworks (e.g., Impressionist paintings).

2. Materials and methods

2.1. Image datasets

An overview of all datasets used in the present study and their sources is provided in Table 1. Previously published and novel datasets of images were analysed. Previously published datasets included the JenAesthetics dataset (Amirshahi, Hayn-Leichsenring, Denzler, & Redies, 2015), which consists of 1629 high-quality images of oil paintings that were made available by museums around the world through the Google Art Project (Set No. 1 in Table 1). This dataset comprises paintings from major periods of Western art, extending from the Renaissance to Expressionism, but excluding postmodern and contemporary art. The paintings depict various subject matters, including landscapes, seascapes, urban scenes, still lives, portraits, nudes, and architecture. For comparison, we analysed nine datasets of photographs of man-made patterns and scenes (photographs of simple objects, building facades and urban scenes), passport-type face photographs, and natural scenes and patterns (photographs of large-vista natural scenes, plant patterns, lichen growth patterns, clouds and branches). These datasets (Sets No. 2–10 in Table 1; see examples in Fig. 1) were chosen because they display a wide diversity of statistical image properties, such as complexity, self-similarity and anisotropy (Amirshahi, Redies, & Denzler, 2013; Braun et al., 2013; Redies et al., 2012).

To examine the possibility that some of the observed differences in image statistics are due to differences in the content matter shown in the images, we directly compared photographs and artworks of similar image content. To this aim, we analysed two datasets of face photographs and a dataset of artistic face portraits. The first photographic dataset comprised monochrome versions of 200 faces with neutral facial expressions on a white background (Set No. 5 in Table 1; Martinez & Benavente, 1998). The second photographic dataset consisted of 201 images that were randomly chosen from the Yale dataset of photographs of faces in front of various office backgrounds (Set No. 11 in Table 1; Georghiades, Belhumeur, & Kriegman, 2001). The dataset of artistic face portraits was described previously (Set No. 12 in Table 1; Redies, Hänisch et al., 2007); it comprised 306 monochrome images and represented various graphic techniques and different art genres of Western provenance from the 16th to the 20th centuries (see examples in Suppl. Fig. S1a,b). Moreover, we compared photographs of Dutch natural scenes (Set No. 13 in Table 1; see example in Suppl. Fig. S1c; van Hateren & van der Schaaf, 1998) with a series of Dutch landscape drawings and prints (Set No. 14 in Table 1; see example in Suppl. Fig. S1d). To match image content in these two datasets more closely, we also used 150 pairs of images that were selected from these two datasets in a previous study (Koch, Denzler, & Redies, 2010), in which five participants were instructed to pick 30 pairs each of landscape photographs and artworks that closely matched each other in image content.

In order to extend our analysis to artworks produced by different artistic techniques and to artworks from other cultural backgrounds, we analysed datasets of graphic artworks of Western provenance (Set No. 15 in Table 1; see example in Suppl. Fig. S1e) and diverse sets of artworks from East Asian and Islamic cultures (Sets No. 16–20 in Table 1; see examples in Suppl. Fig. S2a-e).

Finally, we extended our analysis to colour-opponent edges. Beside some of the datasets mentioned above, we analysed 296 highly colourful artworks that included Impressionist, Neo-Impressionist and Post-Impressionist paintings (Set No. 21 in Table 1). These images were downloaded from the Wikimedia