Perception of Symmetry in Natural Images

A Cortical Representation of Shape

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Abstract. Symmetry has long been considered as an influential Gestalt factor for grouping and figure-ground segregation. As natural contours are not precisely symmetric in terms of geometry, we proposed a quantification of the degree of symmetry (DoS) that is applicable for arbitrary contours in natural images. DoS showed an agreement with the perception of symmetry in judgment of symmetry axis. Multi-dimensional scaling, together with similarity tests among natural contours, showed that DoS is a quantitative perceptual measure that accounts for the shape of contour. These results indicate that DoS reflects the perception of symmetry in natural contours, and further suggest that DoS is a plausible candidate for representing shape in the cortex.

Keywords: vision, perception, cognitive science, cortical representation, natural image, visual psychophysics.

1 Introduction

Gestalt factors, such as convexity, closure, parallel and symmetry, have been known as cues for grouping and figure-ground segregation that are crucial bases for the perception of shape and object. Symmetry has long been considered as an influential Gestalt factor because symmetry is frequently observed among living creatures and artificial products [e.g., 1, 2]. However, natural contours are not precisely symmetric in terms of geometry, thus no quantitative analysis on symmetry has been studied with natural images. Quantification of *the degree of symmetry* needs to be proposed for investigating the perception in natural images. Focusing on symmetry in natural contours, we established a computational index that describes the degree of symmetry (DoS) inherent in arbitrary contours. DoS was computed based on the degree of the overlap of contours between two sub-images divided by the optimal symmetry axis that was searched thoroughly. Our psychophysical experiment showed that the proposed DoS agreed with the perception of symmetry in the judgment of symmetry axis. To assure that DoS is a quantitative perceptual measure, we performed similarity tests between a variety of natural contour patches, and analyzed whether DoS accounts for the similarity. Multi-dimensional scaling (MDS) analyses showed that DoS, together with convexity and closure, is indeed a perceptual measure. These results indicate that DoS reflects the perception of symmetry in natural contours. Together with the recent evidence on adaptation [3], our result also supports the cortex representation of

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symmetry as a basis for shape perception. The proposed DoS will greatly help studying symmetry in the perception of natural images.

2 Quantification of Symmetry

We propose the *degree of symmetry* as a quantitative measure to describe how much a local contour is close to the axial symmetry. Because natural contours are barely symmetric in terms of geometry, quantification of the degree of symmetry needs to be proposed for investigating the perception in natural images. We established a computational index that describes the degree of symmetry inherent in arbitrary contours.

2.1 Definition of the Degree of Symmetry

We consider the degree of symmetry for local contour patches. The degree of symmetry is computed based on the degree of the overlap of contours between the two sides divided by the optimal symmetry axis, as illustrated in Fig. 1. We thoroughly search the optimal symmetry axis, by rotating and translating the axis and computing the overlap of contours between the two sides. The axis is represented by the rotation, θ, and the translation in x. Note that the axis could be placed anywhere in the patch. The overlap of contours between the two sides (a & b) is given by:

$$dos_{\theta,x} = \frac{\sum_{i=1}^{(N-1)/2} \left(\sum_{j=1}^{(N-1)/2} \left(a_{ij} b_{((N-1)/2)+1-i,j} \right) \right)}{length} \qquad \text{Eq. 1}$$

where i and j correspond to x and y directions of the rotated/translated patch, respectively, with the origin at the left-top corner. Note that the original patch is rotated and translated so that the symmetry axis is vertical and located at the center. N is the spatial extent of the patch in pixel (N=69 throughout this article). The degree of overlap is normalized by the length of contour in the patch (*length*). The optimal symmetry axis of a patch, which is described by θ and x, is given by: 1

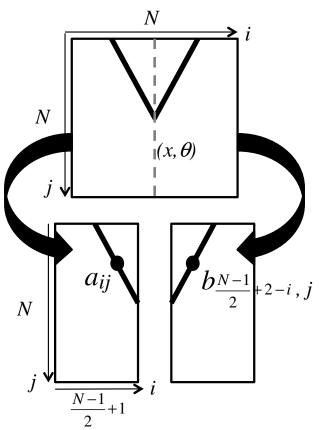

Fig. 1. An illustration of the computation of DoS. A contour patch (top) was divided by an axis (dotted line). DoS was given by the degree of the overlap of the contours between the two sides (bottom panels). If a contour is perfect symmetry, DoS is one.

$$\boldsymbol{OSA} = \text{argmax}(dos_{\theta,x}) \qquad \text{Eq. 2}$$

We normalize *dos* by the largest *dos* (max(*dos*)) among 1302 patches taken from Berkeley Segmentation Dataset (BSD) [4] (see section 3.1), and define it as the degree of symmetry of the patch (*k*) :

$$DOS_k = \frac{dos_{OSA,k}}{\max\limits_k(dos_{OSA,k})} \qquad \text{Eq. 3}$$

We confirmed that the patch with DoS=1 showed perfect symmetry.

2.2 Degree of Symmetry in Natural Contours

We computed DoS for the patches from BSD, as a few examples of the optimal symmetry axis and DoS shown in Fig. 2. From visual inspection, the optimal axes and DoS appear to naturally represent symmetry. The distribution of DoS for all patches ranged between about 0.4 and 1.0, as shown in Fig. 2. In the following sections, we examine quantitatively whether the optimal axis and DoS agree with the perception of symmetry. If DoS is the perceptual measure of symmetry, it will suggest the cortical representation of symmetry in a form similar to DoS.

3 Perception of Symmetry

We defined DoS as a computational measure of axial symmetry applicable for arbitrary contours in natural images. In this section, we examine whether DoS agrees with the perception of symmetry. Specifically, we performed psychophysical experiments to test whether the optimal symmetry axis derived by DoS matches with the human judgment of symmetry axis.

3.1 Methods

We performed psychophysical experiments to obtain the perceptual axis of symmetry in natural contours. We presented a series of contour patches taken from natural

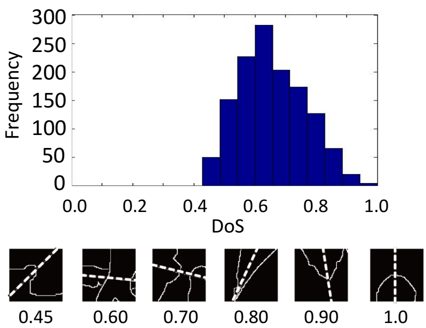

Fig. 2. Six examples of contour patch, DoS and the optimal symmetry axis (dotted lines) determined from DoS (bottom). A contour with higher DoS appears more symmetric. The histogram of DoS (top).

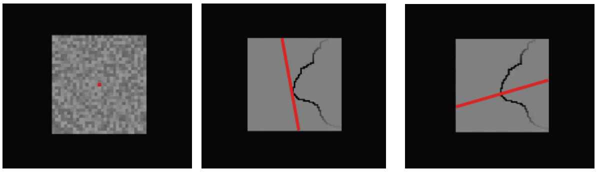

Fig. 3. An illustration of the experimental procedure. Following a mask (left), a contour patch together with a probe bar (red solid line) was presented (center). Participants rotated and translated the probe (right) to indicate the line that is most likely the symmetry axis.

images [4], and asked participants to determine a symmetry axis. The experimental procedure is illustrated in Fig. 3. We chosen systematically 1302 patches from BSD so that their curvature and closeness varied for a wide range. A single patch of 4x4 degrees in visual angel was presented on a liquid crystal display. Participants placed a bar as if it constitutes the best symmetry axis. Nine participants with normal or corrected-to-normal vision in their age of twenties repeated the task twice, therefore 18 axes were obtained for each patch. The experiment was approved by the research ethical committee of the institute.

3.2 Perception and the Degree of Symmetry

The perceptual axes of symmetry were obtained for the 1302 patches of natural contours, and compared with the optimal axes determined by DoS, as a few examples shown in Fig. 4(Left). Perceptual axis often varied among participants and trials, in such a case, multiple axes would represent the perceptual symmetry of a patch. To evaluate the consistency of the axis among trials and participants, we defined the *consistency* that is given by the degree of overlap among the axes. The consistency is one if all 18 axes are identical. A few examples and the distribution of the consistency are shown in Fig. 4(Right).

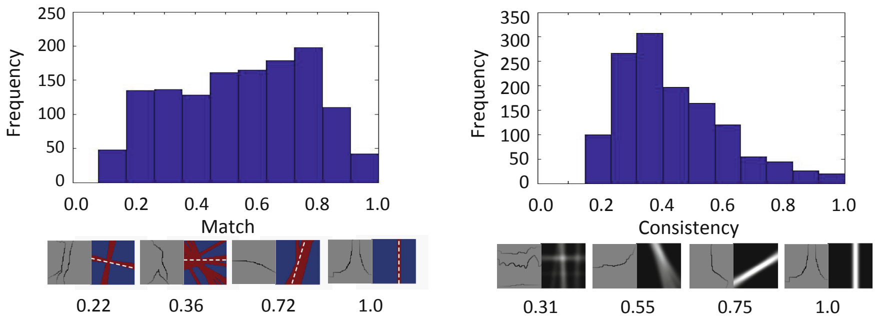

Fig. 4. Left: The histogram of the match between the computed and perceived axes (top). The bottom panels show four examples of contour (left), the computed axis (dotted lines) and the perceived axis (red solid lines). Right: The histogram of the consistency (top), and four examples of contour and superimposed perceptual axes (bottom).

We analyzed how often the computed axis matches with the perceptual axis. The histogram of the match (Fig. 4(Left)) shows a wide distribution, which would indicate that DoS does not match with perception in many cases. However, note that the patches consisted of a wide range of contours including those do not appear symmetry. Because the participants were forced to place an axis for all patches, the analysis should disregard those patches without symmetrical contours. It is difficult to rank the degree of symmetry without DoS. We come to utilize the consistency of axis as a measure to disregard non-symmetric contours. Because the consistency should be low if participants barely perceive symmetry in a patch, and high if they clearly perceive symmetry. We examined whether the match increases as the consistency increases. If this is the case, DoS can be considered as it correctly reflects the perception. We plotted the match as a function of consistency, as shown in Fig. 5. We observe a clear tendency that match increases with the consistency. Most of patches with the consistency > 0.6 show the match > 0.8. These results show that the proposed DoS agrees with the perception of symmetry.

4 Perceptual Representation of Symmetry --- Similarity Judgment of Contours ---

To assure that DoS is a quantitative perceptual measure, we determined psychophysically the multi-dimensional configuration that represents the perceptual shape of local contour, and analyzed whether DoS could be an axis of the configuration. Specifically, we performed similarity tests between a variety of natural contour patches, and analyzed whether DoS accounts for the similarity by multi-dimensional scaling (MDS) analysis.

4.1 Methods

We performed psychophysical experiments to obtain perceptual similarity of local, natural contours. We presented a pair of the contour patches, following a mask with a fixation aid, as shown in Fig. 6. We chose 54 patches from those used in the previous

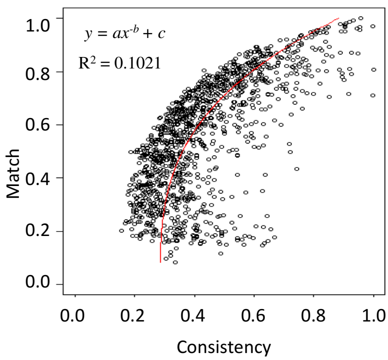

Fig. 5. The match between the computed and perceived axes as a function of the consistency. As the consistency increases, the match increase. The coefficient of determination for the nonlinear regression is shown in the inset.

experiment (section 3.1). The patches were chosen by visual inspection so as to assure a wide variety in contour shape. All pairs of the patches (1431) were presented in a random order. Six participants judged the similarity of pairs by the subjective scaling method with 5 ranks. The other experimental conditions were similar to those in 3.1. We calculated the perceptual similarity between all pairs of patches for each participant.

We applied MDS [5] to the perceptual similarity between the pairs of patches, and obtained the spatial configuration of the perception in 1 and 2 dimensions. This configuration provides coordinates for all patches, in which similar patches are close to each other, and dissimilar patches are distant. Thus, the spatial configuration represents the perception of natural contours.

4.2 Multi-Dimensinal Scaling Analysis

We tested whether the perceptual configuration (PC) of the patches agrees with the configuration of DoS (DC). For instance, the two-dimensional (2D) PC has two axes, meaning that contour shape can be described by two factors. We examined whether one of the factor could be DoS. We computed the overall pair-wise Euclidian distance of patches between the PC and DC, following the minimization of the distance by the Procrustes rotation method. We performed statistical tests to examine whether the distance between the PC and DC was significantly smaller than the distance between the PC and the random configuration. We carried out the test for each participant. For 1D configuration, 3 out of 6 participants showed a significant difference between PC-DC and PC-random distances. The result indicates that DoS accounts for the similarity in natural contours in half of participants with 1D configuration.

As we discussed in the previous section, the patches consisted of a wide range of contours including those do not appear symmetry. For this reason, we introduced another axis (factor) that would account for the similarity [6, 7]. We used either convexity or closeness in addition to DoS, and performed 2D analysis. The statistical tests showed that all participants showed a significant difference between PC-DC and PC-random distances in both cases (convex-DoS & closeness-DoS), as summarized in Table 1. These results show that DoS accounts for the similarity in natural contours, indicating that DoS reflects the perception of symmetry in natural contours.

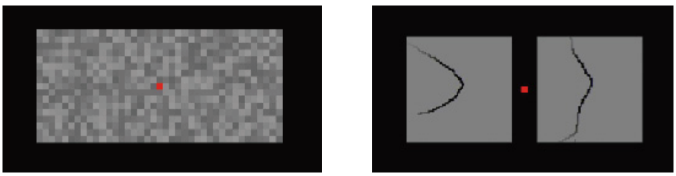

Fig. 6. An illustration of the experimental procedure for the similarity test. Following a mask with a fixation aid (left), a pair of patch was presented (right). Participants judged the similarity between the patches by the subjective scaling method with 5 ranks.

Table 1. Summary of the statistical tests for 1D and 2D configurations in MDS analysis

1 dimension	2 dimensions
Symmetry 3/6 participants were significant	Symmetry & Closure 6/6 were significant
	Symmetry & Convexity 6/6 were significant

5 Conclusions and Discussions

We proposed a computational index, DoS, that describes the degree of symmetry inherent in arbitrary contours. Our psychophysical experiment showed that DoS agrees with the perception of symmetry in the judgment of symmetry axis. To assure that DoS is a quantitative perceptual measure, we performed similarity tests between a variety of natural contour patches, and analyzed whether DoS accounts for the similarity. MDS analyses showed that DoS, together with convexity and closure, is indeed a perceptual measure. These results show that DoS accounts for the similarity in natural contours, indicating that DoS reflects the perception of symmetry in natural contours. Together with the recent evidence on adaptation [3], our result supports the cortex representation of symmetry as a basis for shape perception.

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References

[1] Hung, C.C., Carlson, E.T., Connor, C.E.: Medial axis shape cording in Macaque inferotemporal cortex. Neuron 74, 1099–1113 (2012)

[2] Hatori, Y., Sakai, K.: Early representation of shape by onset synchronization of border-ownership-selective cells in the V1-V2 network. J. Opt. Soc. Am., A 31, 716–729

[3] Gheorghiu, E., Bell, J., Kingdom, F.A.A.: Visual adaptation to symmetry. VSS 2014 23, 227 (2014)

[4] Martin, D., Fowlkes, C., Tal, D., Malik, J.: A database of human segmented natural images and its application to evaluating segmentation algorithms and measureing ecological statistics. Proc. ICCV 2, 416–423 (2001)

[5] Kruscal, J.B.: Multidimensional scaling by optimizing goodness of fit to a nonmetric hypothesis. Psychometrika 29, 1–27 (1964)

[6] Fowlkes, C.C., Martin, D.R., Malik, J.: Local figure-ground cues are valid for natural images. J. Vision 7(8), 2 (2007), doi:10.1167/7.8.2

[7] Sakai, K., Nishimura, H., Shimizu, R., Kondo, K.: Consistent and robust determination of border ownership based on asymmetric surrounding contrast. Neural Networks 33, 257–274 (2012)