Dry, Matthew James
Mirror symmetry perception: the effect of proximity to the central axis Proceedings of the 27th Annual Conference of the Cognitive Science Society / Bruno G. Bara, Lawrence Barsalou, & Monica Bucciarelli; pp. 612

Mirror Symmetry Perception: The Effect of Proximity to the Central Axis

Matthew Dry (matthew.dry@psychology.adelaide.edu.au)
Department of Psychology, University of Adelaide
Adelaide, SA 5005 Australia.

Abstract

The detection of environmental regularity is a fundamental process in visual perception. One way of increasing our understanding of the visual system is by modelling the performance of human observers on tasks in which they are required to detect visual regularities such as bilateral symmetry. Past research has indicated that there is a perceptual advantage for symmetry information located immediately adjacent to the central axis (Barlow & Reeves, 1979; Rainville & Kingdom, 2002), but it has been unclear whether this was due to the temporal or spatial properties of the stimulus. Three potential outcomes were hypothesised in relation to a symmetry detection task and Bayesian model selection was used to determine which outcome best accounted for the empirical data. Results indicate that when temporal limitations are removed the perceptual advantage remains, suggesting that it is due (at least in part) to the spatial properties of symmetrical stimuli. The research reported in this paper was conducted at the University of Adelaide.

Introduction

The visual system is extremely efficient at detecting environmental regularity and it has been argued that regularities play a crucial role in our understanding of the visual world (Barlow, 2001). The perception of bilateral (or mirror) symmetry is one example of this regularity detection. Specifically, the visual system can be considered as performing a kind of spatial correspondence calculation whereby it employs the inherent statistical information about the positions of pattern elements to establish which of the elements belong or are grouped together.

Interestingly, it has been demonstrated that observers either fail to make use of, or disregard, a high proportion of the information that is available to them when making psychophysical judgements of symmetry. For example, a number of studies have demonstrated that observers are only able to detect symmetry (or deviations from symmetry) if it is located within a spatially limited region directly adjacent to the axis of symmetry (Barlow & Reeves, 1979; Rainville & Kingdom, 2002). This area has been labelled the Integration Region and it is hypothesised that the visual system is unable to make the correspondence calculations necessary for symmetry detection if signal information is located outside of this region.

It has been noted that symmetry in real-world stimuli can be detected over separation distances much greater than those reported in the majority of psychophysical studies (Labonte, Shapira, Cohen, & Faubert, 1995; Tyler, Hardage, & Miller, 1995). The reason for this discrepancy between real-world and laboratory stimuli appears to be related to the very brief presentation times employed in the majority of studies. For example Tyler, Hardage and Miller (1995) compared detection across presentation times ranging from 20 milliseconds to 2 seconds and found that as stimulus presentation time increased, observers were able to detect symmetry over increasingly larger separation distances.

Although Tyler *et al* found evidence of long-range detection for presentation durations greater than 300ms, the data still indicated greater sensitivity for symmetrical information located close to the central axis. However, it is unclear whether this increased sensitivity bias would remain if the presentation times were increased beyond 2 seconds. If observers were allowed unlimited viewing time it is possible that the advantage conveyed by proximity to the axis would disappear indicating that the advantage is a temporal artefact. If a proximity advantage persisted, regardless of presentation time, this would suggest that it is a feature of the spatial rather than the temporal properties of the stimulus.

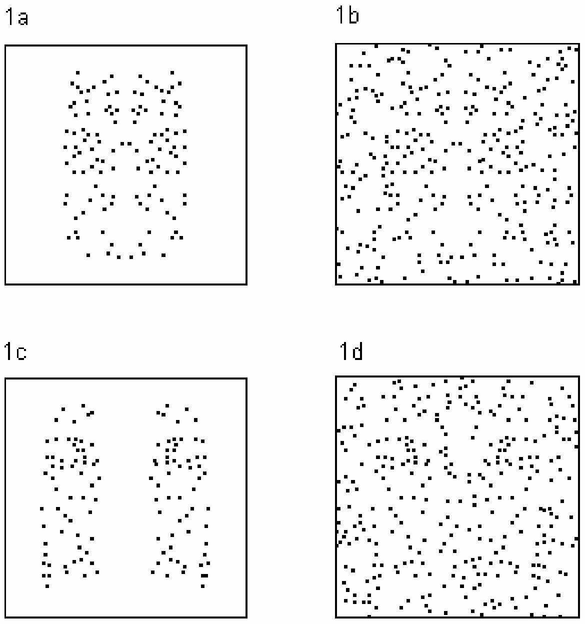

Figure 1: Examples of experimental stimuli and the signal information contained therein. 1a) Signal window containing 100% symmetry and zero separation. 1b) The signal window in 1a embedded in random noise. 1c) Signal window containing 100% symmetry and 1.5 deg separation. 1d) The signal window in 1c embedded in random noise. Experimental stimuli resembled 1b and 1d.

Current Study

The present study sought to determine if there is increased sensitivity for symmetrical information located near the axis when observers have unlimited viewing time. The design of the experimental stimuli was similar to that employed in a number of previous studies (e.g. Rainville & Kingdom, 2002). Observers were required to discriminate between random dot 'noise' stimuli, and stimuli that contained a proportion of symmetrical pairings embedded in noise. The symmetrical information was confined to two equally sized areas, or 'signal windows', situated on either side of the axis of symmetry. In order to determine the relationship between discriminability of symmetrical pairings and the proximity of these pairings to the axis of symmetry, the distance between the two areas containing symmetrical information was manipulated, and the resulting gap filled with random noise. Figure 1 provides examples of the types of test stimuli used in the experiment. Furthermore, in order to demonstrate the effect of varying the signal-to-noise ratio of the stimulus upon discriminability, three levels of signal-to-noise ratio were employed.

In light of the above, a number of predictions about experimental outcomes follow. First, if there is no relationship between discriminability and the proximity of symmetrical pairings to the axis we could expect the results to resemble three flat functions layered in order of their respective signal-to-noise ratios. This situation we call the "No Proximity Advantage" model and its predictions are shown graphically in Figure 2a. Second, if an advantage is associated with proximity to the axis even when the observers are allowed unlimited viewing time then this advantage might be expected to decline gradually as the symmetry separation distance is increased. In this case detection would be a linear function of distance from the axis and would result in three linear functions. This situation we call the "Linear Proximity Advantage" model and its predictions are shown graphically in Figure 2b. Third, it is possible that there would be an advantage conveyed by proximity, but this advantage would be confined to a limited region. This would result in a series of three two-limbed functions in which discriminability is high when symmetry pairings directly span the axis, but uniformly poor across all other separation distances. This situation we call the "Short-Range Proximity Advantage" model and its predictions are shown graphically in Figure 2c.

Methods

Apparatus and Stimuli

All stimuli were presented on a Hitachi CM721F colour computer monitor with a refresh rate of 85 Hz and a pixel resolution of 1280 x 1024. Pixel width was 0.2644 mm. Viewing distance was set at 57 cm, such that 1 cm was equal to 1 degree of visual angle.

The stimuli were comprised of black dots with a diameter of 0.04 deg presented on a 5x5 deg white field located at the centre of the monitor. Dot density was 12 points per degree of visual angle squared (300 points in total). In order to prevent individual points from touching or overlapping a minimum separation distance of 0.099 deg was imposed.

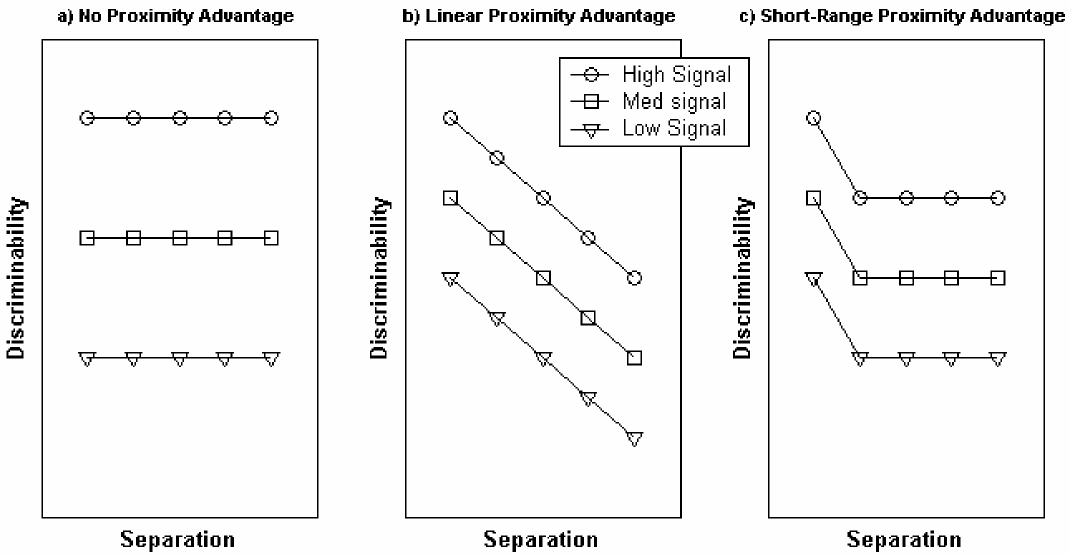

Figure 2: Idealised representation of three potential experimental outcomes. 2a) there is no relationship between discrimination and proximity to the axis of symmetry, 2b) there is a linearly decreasing relationship between discrimination and proximity to the axis, 2c) there is heightened discrimination conveyed by proximity to the axis over a spatially limited region.

The signal pairings within each symmetrical stimulus were confined to two regions or 'signal windows' 1.25 deg wide and 4 deg high. The separation distance between the two signal windows ranged from 0 to 2 deg in four 0.5 deg steps. The symmetrical regions contained 100%, 80% or 60% symmetrical pairings. Given that 40% of all points within a given stimulus were located within the signal windows, this brought the overall percentage of signal pairings within the symmetrical stimuli to 40%, 32% and 24% respectively. Hereafter, however, the three levels of signal to noise ratio will be referred to in terms of the proportion of symmetrical pairings within the two 1.25 x 4 deg windows. The signal pairs were always vertical bilateral (mirror) symmetry pairs with an axis centered in the middle of the stimulus.

Design and Procedure

Observers attended a single test session in which 150 stimulus arrays were presented, half of which were random 'noise' arrays and half 'symmetry and noise' arrays. Of the 75 symmetrical arrays 25 had signal windows containing 100% symmetrical pairings, 25 had signal windows containing 80% signal pairings and 25 had signal windows contained 60% signal pairings. The three signal levels (100%, 80% and 60% signal pairings) contained 5 stimuli at each of the 5 signal window separation distances. The arrays in each test session were presented in a random order. Each test session was preceded by a practice session.

Each array was presented until the observer made a decision and they were free to actively search each pattern. The observer was required to discriminate between the stimuli comprised entirely of noise and stimuli that contained a proportion of symmetrical pairings embedded in noise. They indicated their decision via a mouse click on one of two buttons labelled "Random" and "Symmetrical" that were located below the presentation window.

Observers

There were five observers (two male, three female), with a mean age of 25.4 years. All were studying at tertiary level. The subjects all had either normal or corrected to normal vision. All observers were naïve with respect to the hypothesised outcomes.

Results

Overall performance was high with observers responding correctly to 71.6% of the 150 test stimuli. Figure 3 shows the mean discriminability of symmetrical stimuli measured as *d'* for all five observers across the three signal levels and five separation distances. Values of *d'* were calculated following Green and Swets (1974). Although there is a small degree of overlap, there is a clear ordering of discriminability in terms of the overall level of symmetrical pairings. Additionally, the results suggest that when the proportion of symmetrical pairings within the signal windows was at its highest (100%), the observers were able to discriminate between symmetrical and noise stimuli with a *d'* greater than 2 regardless of the degree of spatial separation between the signal windows. Even when the proportion of signal pairs was reduced to 80%, *d'* was above or close to 1.

Qualitatively, the results appear to indicate that discriminability is high when symmetry pairings directly straddle the axis, but is uniformly degraded across all other separation distances. The obvious exception to this pattern is the increased discriminability for stimuli with a separation of 2 deg and 100% symmetry in the signal window. The 2 deg separation places the outside edge of the signal window within .25 deg of the stimulus boundary. It should be noted that Barlow and Reeves (1979) found a similar U-shaped relationship, with detection being best for symmetrical structure positioned at the axis, middling for structure positioned at the stimulus boundary, and worst for structure flanked on both sides by noise.

Bayesian statistical inference (Kass & Raftery, 1995) was employed to determine which of the three predicted outcomes summarised in Figure 2 best accounted for the empirical data, largely following the approach adopted by Vickers, Lee, Dry and Hughes (2003). Using this method the three outcomes become competing models that make different assumptions about the relationship between discriminability and proximity to the central axis. Figure 4 shows the maximum likelihood fits to *d'* under each of the three models, assuming a Gaussian likelihood function.

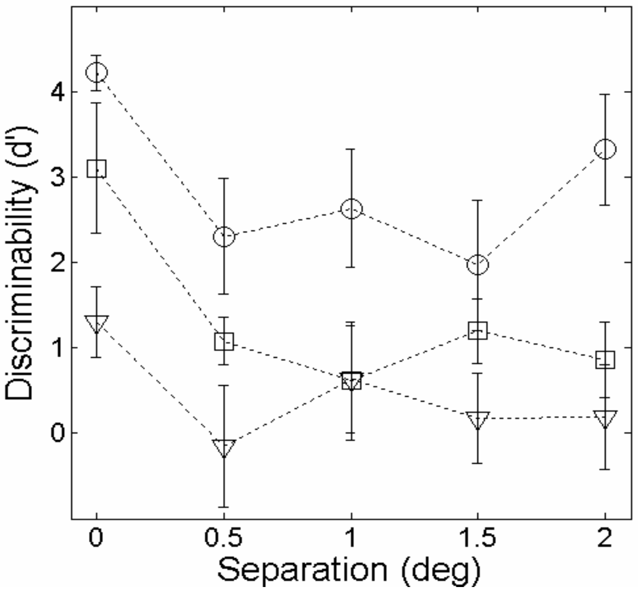

FIGURE 3. Mean discriminability of symmetrical stimuli measured as *d'* for all five observers across the three signal levels and five separation distances. Circles denote 100% symmetry in signal window, squares denote 80% symmetry in signal window, and triangles denote 60% symmetry in signal window. The numbers on the x-axis indicate the distance in deg between the two signal windows (areas containing symmetrical pairings). Errorbars represent the standard error of observer *d'*.

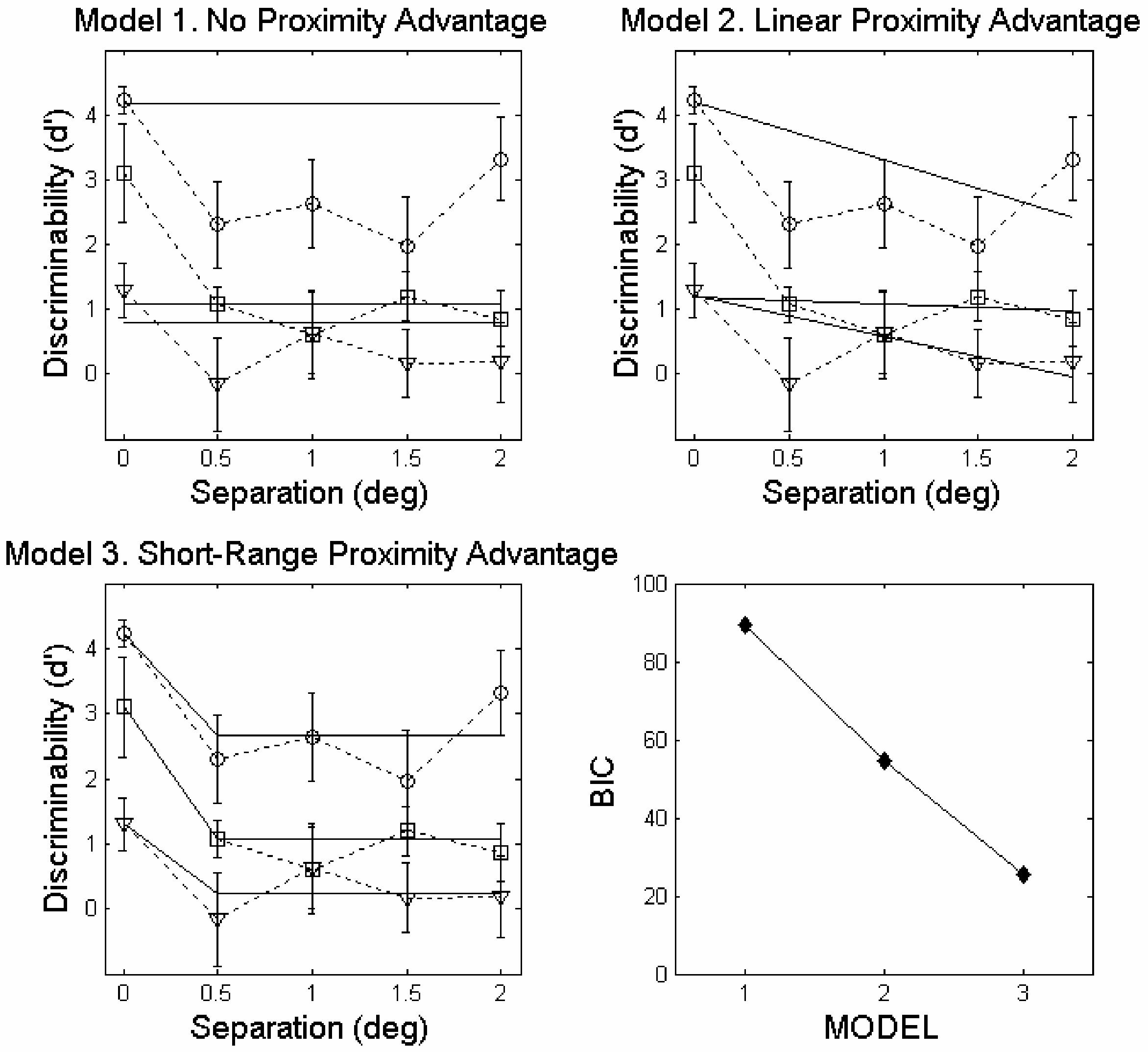

Figure 4: Summary of fit to empirical data for the three models, and the associated BIC. Circles denote 100% symmetry in signal window, squares denote 80% symmetry in signal window, and triangles denote 60% symmetry in signal window. The x-axis indicates the minimum separation distance between symmetrical pairings. Error bars represent the standard error of *d'* across the five observers.

Table 1: The Maximum Likelihood Fit, Parametric Complexity, Bayesian Information Criterion (BIC) Value, and Bayes Factors for Each of the Models in Relation to *d'*.

Model	Maximum Likelihood Fit	Parametric Complexity	BIC Value	Bayes Factor
1. No Advantage	81.3977	3	89.52	8x10^{13}
2. Linear Advantage	38.2941	6	54.54	2x10^{6}
3. Short-Range Advantage	9.0398	6	25.28	1.00

Note- The Bayes Factors are taken in relation to the most likely model, which in this case is the Short-Range Proximity Advantage model.

Given these data fits and the known parametric complexity of the models, it is possible to calculate the Bayesian Information Criterion (BIC) for each model (Schwarz, 1978). The relative likelihood of each model can then be determined by calculating Bayes Factors (Kass & Raftery, 1995). Table 1 summarizes the results of the analyses, showing the maximum likelihood fit of the three series predicted by each model, the number of model parameters, and the BIC and Bayes factors. The Bayesian analyses indicate that the data provide the most evidence for the Short-Range Proximity Advantage model, with the Linear Proximity Advantage model being about 2×10^6 times less likely, and the No Proximity Advantage model being about 8×10^{13} times less likely. It should be remembered that this does not suggest that the Short-Range Proximity model provides the sole plausible explanation for the data, but merely indicates that of the three models tested, the No Proximity Advantage and Linear Proximity Advantage models can be discounted as less likely explanations than the Short-Range Proximity Advantage model.

Discussion

The structure in symmetrical dot stimuli can be described as a distribution of uniformly oriented pairs of points with collinear midpoints, and it has been suggested that it is these first-order regularities that the visual system is perceiving during symmetry detection tasks (Jenkins, 1983). However, the results of this study suggest that not all point-pairs contribute equally to the perception of structure or order; therefore a model of symmetry perception based on orientation and collinearity information alone is not sufficient to explain the pattern of observer responses typically found in symmetry detection tasks.

Past research has indicated that there is a perceptual advantage for symmetry information located immediately adjacent to the central axis but it has been unclear whether this was due to the temporal or spatial properties of the stimulus. The present study has demonstrated that when temporal limitations are removed the perceptual advantage remains. This indicates that the advantage is due, at least in part, to the spatial properties of symmetrical stimuli.

A distinction between the present study and the majority of previous research is the finding that, when the proportion of symmetrical information within the signal windows was high, observers are able to make correspondences between symmetrical point pairs regardless of their spatial separation. Given that the task conditions allowed both unlimited viewing time and free visual search it is hardly surprising that the observers were able to detect symmetry pairings located outside of the strictly delimited region implicated in previous research. Nevertheless, it is not immediately obvious why point-pairs located directly adjacent to the axis should appear more salient than all other signal pairings.

Wertheimer (1938) recognized the role of proximity as a primary organizing principle in visual perception, and the data appear to indicate some form of relationship between detectability and point-pair separation. However, the analysis of model fit to empirical data suggests it is unlikely that a detection rule based on proximity alone can account for the observer responses: The Linear Proximity Advantage model, in which detectability declines as a function of distance from axis was found to be far less likely than the Short-Range Proximity Advantage model. Furthermore, there is evidence suggesting that the size of the region of increased sensitivity scales inversely with stimulus density (Rainville & Kingdom, 2002). This would rule out the possibility of a detection heuristic based on heightened sensitivity for signal pairs separated by a fixed or *absolute* distance. It is suggested that a more likely candidate explanation is a detection heuristic based on *relative* distances.

A number of attempts have been made to quantify the gestalt principles of form perception using clustering algorithms such as minimal spanning trees, relative neighborhood graphs, and Voronoi tessellation (Ahuja, 1982). Although there are key differences between these approaches, a common feature is that they are able to define the relationship between each point within a stimulus and every other point within that stimulus in terms of relative distances (for example, in a stimulus containing k points each point in that stimulus will have k-1 neighbors: the nearest neighbor, second nearest neighbor, third nearest neighbor etc). Research has found that the perception of structure within a wide range of dot pattern stimulus classes appears to be highly dependant upon the clusters formed between point pairs with low-level neighbor relations (Dry, Vickers, Lee, & Hughes, submitted; Pomerantz, 1981; Vickers *et al*., 2003), and there is evidence to suggest that symmetry detection is also preceded by some form of localized clustering or grouping of stimulus elements (Labonte *et al*., 1995; Wagemans, Van Gool, Swinnen, & Van Horebeek, 1993).

The results of the present study are plausibly attributed to a difference between the visual system's ability to detect signal point pairs that are low-order neighbors, and its ability to detect signal point pairs that are separated by noise or interference points. Figure 5 illustrates this difference. Figure 5b shows the clusters formed by joining each point in Figure 5a to its nearest neighbor. A high proportion of the neighbor clusters span the axis of symmetry and join signal pairs. Figure 5c shows a stimulus with a 0.5 deg signal window separation, and Figure 5d the clusters formed by joining each point in 5c to its nearest neighbor. As can be seen, none of the signal pairs in 5d form a nearest neighbor cluster. Symmetrical structure is still detectable, but only via long-range comparisons of the clusters.

A similar process appears to be at work during the perception of structure in Glass patterns (Glass, 1969). Glass patterns are produced by subjecting an array of random dots to a uniform geometric transformation and superimposing the transformed array on the original. A distinction has been made between the high detectability of Glass pattern point-pairs that are low-order neighbors, and the less easily detected 'striation' caused by increasing inter-point distance such that there are a number of interference points that lie between the two points in a signal pair (Stevens, 1978). Nearest neighbour relations have been used to model structure detection and discrimination in Glass patterns (Dry *et al*., submitted), and a similar model should be able to account for the perception of structure in symmetrical stimuli.

It is recognized that the research presented in this paper is preliminary and more data is needed before firm conclusions can be made about the nature of the spatial features exploited by the visual system when detecting structure in symmetrical stimuli. However, the data provided by this study, in conjunction with the results of a number of previous studies (Labonte *et al*., 1995; Tyler *et al*., 1995), have important implications for the future development of models of symmetry detection. Recent models of symmetry detection have tended to focus solely upon detecting structure located at the axis of symmetry. This paper adds to the body of research suggesting that a plausible model of symmetry detection must be capable of detecting structure across a wide range of separation distances.

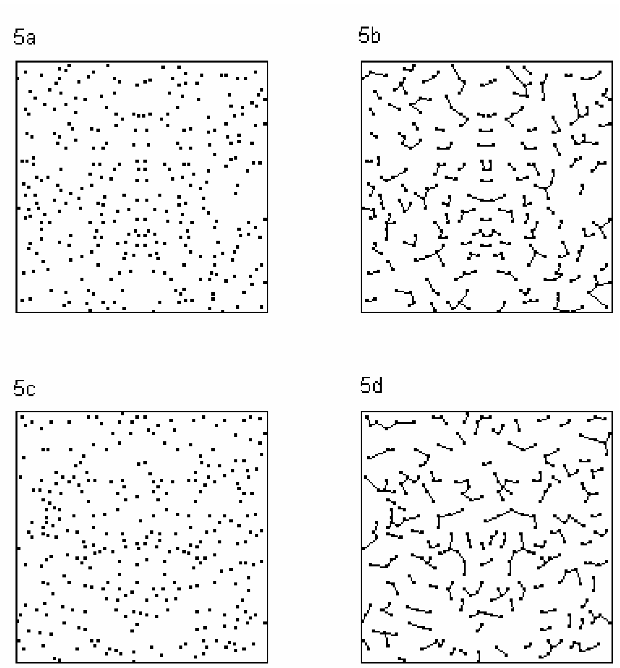

Figure 5: Examples clustering formed by joining nearest neighbors. 5a) Stimulus with a signal window containing 100% symmetry and zero separation. 5b) Clusters formed by joining each point in 5a to its nearest neighbor. 5c) Stimulus with a signal window containing 100% symmetry and 0.5 deg separation. 5d) Clusters formed by joining each point in 5c to its nearest neighbor.

Acknowledgements

I thank Douglas Vickers and Nick Burns for their advice, and Michael Lee for his invaluable programming assistance and advice concerning the analyses.

References

Ahuja, N. (1982). Dot Pattern Processing Using Voronoi Neighborhoods. *Ieee Transactions on Pattern Analysis and Machine Intelligence, 4*(3), 336-343.

Barlow, H. (2001). The exploitation of regularities in the environment by the brain. *Behavioral and Brain Sciences, 24*(4), 602-607.

Barlow, H. B., & Reeves, B. C. (1979). The versatility and absolute efficiency of detecting mirror symmetry in random dot displays. *Vision Research, 19*, 783-793.

Dry, M. J., Vickers, D., Lee, M. D., & Hughes, P. (submitted). The role of nearest neighbors in the perception of Glass patterns.

Glass, L. (1969). Moiré Effect from Random Dots. *Nature, 223*, 578-580.

Green, D. M., & Swets, J. A. (1974). *Signal Detection Theory and Psychophysics*. New York: Krieger.

Jenkins, B. (1983). Component processes in the perception of bilaterally symmetric dot textures. *Perception & Psychophysics, 34*(5), 433-440.

Kass, R. E., & Raftery, A. E. (1995). Bayes factors. *Journal of the American Statistical Association, 90*(430), 773-796.

Labonte, F., Shapira, Y., Cohen, P., & Faubert, J. (1995). A Model for Global Symmetry Detection in Dense Images. *Spatial Vision, 9*(1), 33-55.

Pomerantz, J. R. (1981). Perceptual Organization in Information Processing. In M. Kubovy & J. R. Pomerantz (Eds.), *Perceptual Organization*. NJ: Lawrence Erlbaum.

Rainville, S. J. M., & Kingdom, F. A. A. (2002). Scale invariance is driven by stimulus density. *Vision Research, 42*, 351-367.

Schwarz, G. (1978). Estimating the dimension of a model. *Annals of Statistics, 6*, 461-464.

Stevens, K. A. (1978). Computation of Locally Parallel Structure. *Biological Cybernetics, 29*, 19-28.

Tyler, C. W., Hardage, L., & Miller, R. T. (1995). Multiple Mechanisms for the Detection of Mirror Symmetry. *Spatial Vision, 9*(1), 79-100.

Vickers, D., Lee, M. D., Dry, M. J., & Hughes, P. (2003). The roles of the convex hull and the number of potential intersections in performance on visually presented traveling salesperson problems. *Memory & Cognition, 31*(7), 1094-1104.

Wagemans, J., Van Gool, L., Swinnen, V., & Van Horebeek, J. (1993). Higher-Order Structure in Regularity Detection. *Vision Research, 33*(8), 1067-1088.

Wertheimer, M. (1938). Laws of organization in perceptual forms. In W. Ellis (Ed.), *A Source Book of Gestalt Psychology*. New York: Harcourt.