Spotting differences: How qualitative asymmetries influence visual search

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Abstract

While our current understanding of symmetry perception is based on the perception of exact symmetry, there is increasing evidence that humans are sensitive to approximate or *qualitative* symmetry, which is based on a figure's pattern of similar alignable features rather than its geometric invariance when transformed about an axis. In previous research, alignment-based models of symmetry perception have found support in evidence that *qualitative differences* (which break the pattern of alignment in otherwise symmetric figures) have a disproportionate effect on the accuracy and speed of symmetry judgments. In this experiment, we examine whether the qualitative difference effect occurs in the earliest stage of symmetry detection by testing its effect on visual search. There are two central results. First, this experiment generalizes the results of the earlier experiments to stimuli displayed both foveally and parafoveally, and both filled and unfilled. Second, it shows that qualitative differences influence fixations in visual search, supporting an early role for alignment in symmetry detection.

Introduction

Symmetry is a basic quality of many objects in the visual environment, playing a role in perceptual organization and figure reconstruction (Wagemans, 1995). The form of symmetry we perceive is usually understood to be exact or *quantitative* symmetry, where (for mirror symmetric figures) quantities such as angle and length are identical on both sides of an axis. This understanding of symmetry as exact symmetry has lead to simple but useful models of symmetry detection based on the transformational invariance of a figure. As useful as these models are, they fall short when applied to approximate or *qualitative* symmetry, which is problematic given that many objects in the real world (such as human figures) display approximate symmetry.

The MAGI model of regularity detection (Ferguson, 1994, 2001) attempts to account for qualitative symmetry detection by modeling it as a mapping process that aligns similar qualitative relations and features (such as line intersections and boundary concavities) using a structure mapping process like that used to model similarity and analogical comparison (Gentner, 1983). While MAGI handles exact symmetry as well as transformational invariance, MAGI also readily detects qualitative symmetry, finding the axis and corresponding parts of near-symmetric figures in a way that appears to approximate human performance.

MAGI's performance on qualitative symmetry leads to a testable psychological prediction: that there are two different classes of asymmetry. Deviations from symmetry that change the set of qualitative features may block MAGI's alignment process, allowing quick classification of the figure as asymmetric. In contrast, quantitative deviations from symmetry that break exact symmetry but preserve the set of qualitative features may initially fool the alignment process, requiring additional scrutiny to correctly detect the asymmetry. Thus, humans should judge figures with qualitative differences faster or more accurately than figures with quantitative differences.

We can make this prediction more concrete by considering polygons as our stimuli. If we consider the vertices of a non-uniform polygon, each vertex (feature) has a concavity characteristic (being concave, or convex). Corresponding features match if they match in their qualitative concavity and quantitative value. A polygon contains a *quantitative* difference when a pair of corresponding features has the same qualitative value but differ in their exact value (e.g., both are concave, but one is more concave than the other). A polygon contains a *qualitative* difference if a pair of corresponding features differ in their qualitative value (e.g. one is concave and one is convex).

Exactly this effect was shown for qualitative and quantitative differences in polygons in two experiments by Ferguson, Aminoff, & Gentner (Ferguson, Aminoff, & Gentner, 1996, In preparation). In these experiments, participants judged the symmetry of random 12- and 16-gons displayed for 50 msecs. The results showed that qualitative differences in a stimulus improved participant accuracy and response time. In both experiments, human participants were faster or more accurate at judging asymmetric figures with qualitative differences than with quantitative differences. This result supports use of an alignment process in human symmetry detection.

Human sensitivity to qualitative symmetry early in perception suggests that when we recognize exact symmetry, it may involve an interaction between an alignment process that finds the qualitative symmetry, and a subsequent verification stage that uses these correspondences to verify exact symmetry. Previously, Palmer & Hemenway (1978) have proposed a similar two-stage model to account for the perception of oriented and multiple symmetries. In their framework, a first stage detects one or more potential axes of symmetry, while a second verification stage confirms the correct axis. If we adopt their framework, the alignment process would be the first stage. We note that the qualitative symmetry of a figure, though approximate, should be adequate for guiding visual search during verification.

Additional evidence for a two-stage model of symmetry detection can be found in the *symmetry-based lateral bias effect.* Previous research has shown that visual search patterns for some tasks differ significantly for symmetric and asymmetric figures. Locher and Nodine (1973) recorded participants' eye movements during a complexity judgment task for symmetric and asymmetric polygons. These stimuli were either symmetric about the vertical axis or completely asymmetric (symmetric in no axis). Results showed that for symmetric figures, subjects' fixations were heavily biased to one half of each figure, while fixations for asymmetric figures were unbiased. As noted by M. Corballis (1976), this indicated that some form of symmetry was detected before the first saccade. Again, if we adopt the two-stage framework, this means that we can detect first stage processing by examining the subsequent pattern of visual fixations.

We decided to test this hypothesis using a modification of Locher & Nodine's visual search methodology. If, as suspected in this earlier experiment, the first stage of symmetry detection occurs before the first saccade, then qualitative differences in the figure should not just affect the final accuracy (as in (Ferguson et al., In preparation)) but also the pattern of visual search. By analyzing the pattern of visual search for asymmetric stimuli with qualitative and quantitative differences, it should be possible to isolate this effect, thus providing evidence of an alignment process in the first stage of symmetry detection.

To further generalize the earlier results from Ferguson, Aminoff, and Gentner, we also looked at two critical factors that might influence symmetry detection and visual search patterns. First, the size of the stimuli relative to the foveal area affects the amount of visual information that is available before the first saccade, and so could change the pattern of visual search based on that initial information. An alignment-based model predicts that while added fixations may be required to capture the salient features of the stimulus, the accuracy of judgment should remain, even as size changes. Second, whether the polygon is filled or unfilled may affect the ability to determine the figure-ground information necessary to isolate particular concavities. A filled polygon may assist an alignment-based process by making concavity information more salient or more rapidly available.

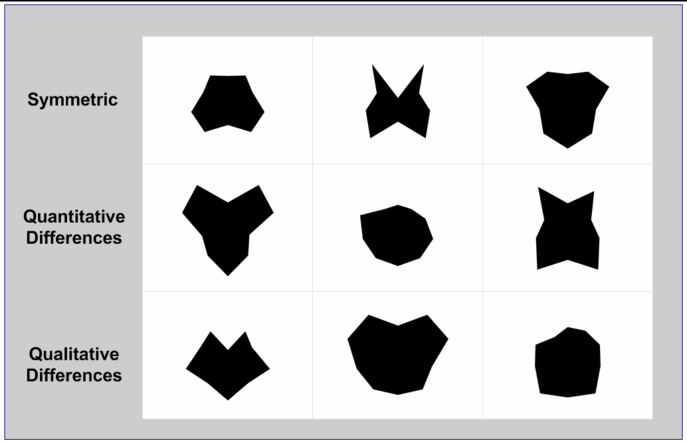

Figure 1: A representative set of stimuli from the experiment. The complete stimulus set was composed of filled and unfilled figures at three sizes for each symmetry type.

Experiment

Method

Participants. 55 university students volunteered to participate in the study for course credit. All participants had normal or adjusted-to-normal vision by self-report. Data from nine subjects were not used in the analysis. Seven subjects were omitted due to a high error rate (more than 8% of samples), while two others were omitted due to calibration errors with the eye-tracker.

Materials. A set of 144 randomly generated polygons was used as experimental stimuli, evenly divided between symmetric polygons, near-symmetric polygons with qualitative differences, and near-symmetric polygons with quantitative differences (Figure 1). Stimuli were shown on a 19 in. monitor set to a resolution of 800x600 pixels and a vertical refresh rate of 60 Hz. Subjects were seated at a viewing distance of 81 cm. At this distance, a 30-pixel radius subtended 2 degrees of visual angle. All stimuli were displayed as black on a white background.

Stimuli were created using the method described in (Palmer & Hemenway, 1978), which was modified to generate polygons that varied according to three independent variables: symmetry quality (symmetric, quantitative asymmetric, and qualitative asymmetric), fill quality, and size with three approximate radii: 50 pixels, 150 pixels, 200 pixels. Qualitative and quantitative differences were generated by randomly selecting one vertex in a generated symmetric shape, which was then changed by a randomly selected amount. The range of the amount differed for each size: ±25 pixels for small, ±50pixels for medium, ±100 pixels for large. Polygons were generated as line drawings that were either filled in or

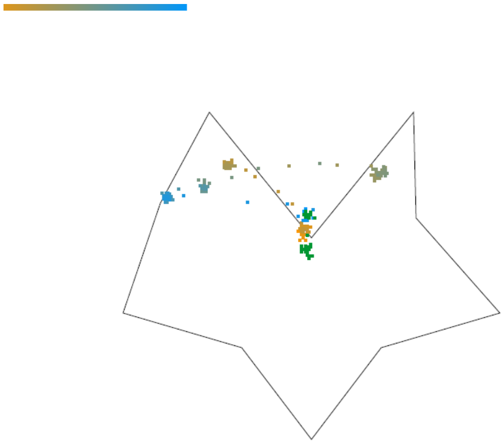

Figure 2: Visual search pattern for single participant. The shading and color (color bar, top) indicates temporal order of samples.

given a 3 pixel line thickness. Three additional stimuli were generated for practice trials.

Design. The design of the experiment was within-subjects with the three independent variables for stimuli: symmetric quality (3), fill (2), and relative distance of features from the center point (3). The dependent variables were accuracy and number of fixations. In addition, we estimated the response time based on the recorded number of samples.

Procedure. The assigned task for each stimulus was to judge whether the polygon was symmetric. Subjects were briefed on the nature of the experiment task and given three practice trials. Before displaying each stimulus, a fixation point was displayed at the center of the screen until fixation on the point was detected in order to center subjects' attention at the stimulus onset, as well as to validate the eye tracking calibration. Stimuli were displayed until subjects made a verbal response to the judgment task, at which point the experimenter advanced to the next trial.

Eye movements during the task (Figure 2) were recorded using a corneal reflection eye-tracking device. Eye positions were sampled at a rate of 120 Hz. A microphone recorded participants' responses. Subjects were given 144 trials, where factors were interleaved. While the order of the stimuli was fixed for all subjects, a one-way ANOVA of mean fixations for the first and second halves of presented experimental stimuli showed no significant difference in distributions (F(1,142)=0.00, p>.9), indicating no learning effect.

Results and Discussion

The results of the experiment are shown in terms of accuracy in the task, response time, and fixations. The accuracy results replicate accuracy results observed in (Ferguson et al., In preparation). Results from an analysis of fixations show how visual search is affected by the symmetry type. To characterize these effects, we calculated the general pattern of fixations using two different methods: as a proportion of fixations on left and right sides of each stimulus and as fixations occurring closest to qualitative or quantitative differences in the near-symmetric figures.

Accuracy. As predicted, a subject analysis showed that participants were significantly more accurate judging asymmetric figures that contained qualitative differences (M=98.10%) than either those with quantitative differences (M=81.66%) or symmetric (M=96.21%) types (Figure 3). (F(2,43)=15.75 p<0.001).

With respect to the size condition, qualitative figures are more accurate than quantitative figures across all size conditions. The untransformed accuracy data also indicate that accuracy for figures with qualitative differences is better than symmetric figures, for both small- and large-size levels. This result is consistent with the use of an alignment model for symmetry detection: qualitative differences give earlier feedback to the participant than quantitative differences, improving accuracy for qualitative differences. The analysis of response time and fixations makes this clearer. An analysis of variance for accuracy showed no effect for fill in individual interactions with symmetry type.

Response Time. The experiment procedure used did not allow for a precise calculation of subject response time. However, we obtained an estimate of response time based on the number of samples collected by the eye tracker. An analysis of samples shows that symmetry type significantly affected the pattern of response times as stimulus size increases. All symmetry types show a steady increase in the number of samples as size increases. The results also show that a greater amount of time is spent on figures with quantitative differences than other symmetry types. Figures with qualitative differences require the least time to analyze, suggesting that a different type of analysis is needed for these figures.

During each trial, subjects were allowed to take as much time as needed to judge symmetry and to allow visual search (M=356 samples, ~3s). When the participant responded vocally, the experimenter pushed a button to stop sampling and present the next stimulus. Although the experimenter attempted to apply the advancement to the next stimulus consistently, the process adds a latent variable

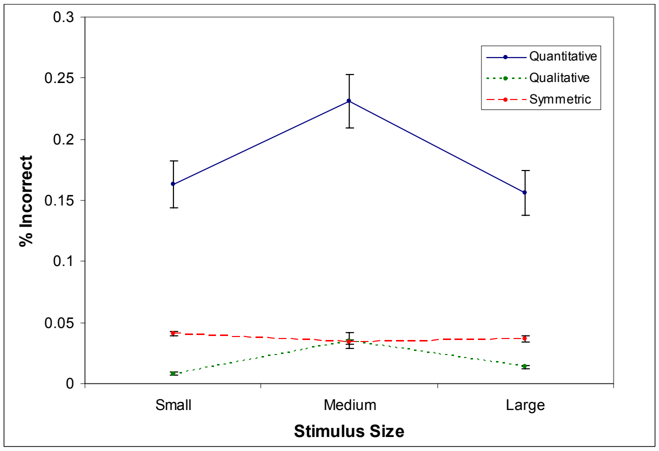

Figure 3: Error rate for symmetry judgments of the three symmetry types at the three stimulus sizes.

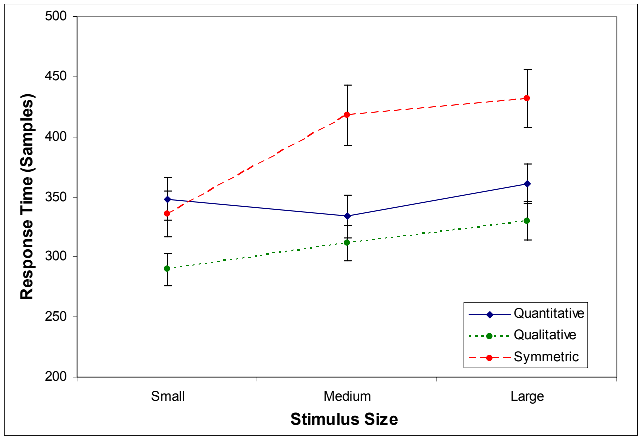

Figure 4: Interval plot of samples for symmetry type as size increases

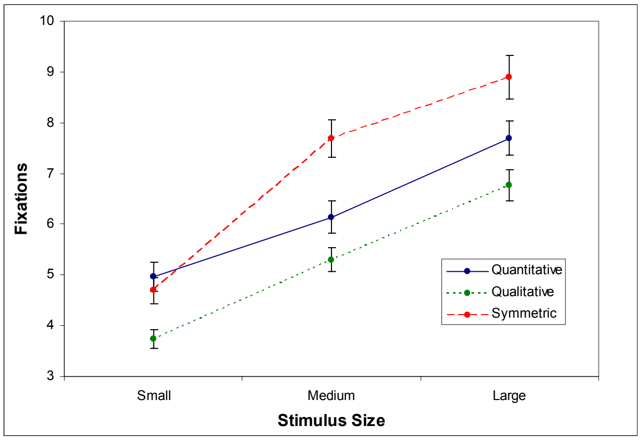

Figure 5: Interval plot of fixation distributions of symmetry type, size factors

to the sample count. In spite of this added variance, the results are still significant (see Figure 4).

An analysis of variance confirms this result. For main effects, participants were faster for qualitative differences than for quantitative differences. They were also faster for smaller than larger stimuli ($F(2,43)=63.07$ $p<0.001$, $F(2,43)=21.82$ $p<0.001$ respectively). Differences for fill were not significant ($F(1,44)=0.05$, *ns*).

Two-way interactions between symmetry type and size were significant ($F(4,40)=8.17$, $p<0.001$). Other two-way interactions were not significant (symmetry type and fill $F(2,43)=0.39$, *ns* and stimulus size and fill $F(2,43)=1.17$, *ns*).

The results for response time add more information to the accuracy results. Subjects are fastest and most accurate when responding to figures with qualitative differences. Subjects take longer to respond to symmetric figures, perhaps because the differences between symmetric figures and figures with quantitative differences are more difficult to discern.

Fixations. The results for fixations parallel those found for response time (Figure 5). A fixation was detected if a minimum of 200ms of samples were in the same location. In general, participants spent more fixations on symmetric figures than the asymmetric figures. Mean fixations were higher for near-symmetric figures when the differences were quantitative rather than qualitative. An analysis of variance for fixations is congruent with the analysis of variance for samples. For main effects, differences in symmetry type and size were significant ($F(2,43)=102.45$, $p<0.001$, $F(2,43)=342.20$, $p<0.001$ respectively). Differences for fill were not significant ($F(1,44)=0.12$, *ns*). For fixations, interactions between symmetry type and size were significant ($F(4,40)=10.64$, $p<0.001$). The interaction between symmetry type and fill was weakly significant ($F(2,43)=2.35$, $p<0.096$). The interaction of stimulus size and fill was not significant ($F(2,43)=1.45$, *ns*).

Effects of fill. Interestingly, fill was not significant as a main effect in either response time or fixation analysis. The two way interactions involving fill also were not significant in both analyses. Three-way interactions for both response time and fixations were significant ($F(4,41)=6.00$, $p<0.001$ and $F(4,41)=4.03$, $p<0.003$ respectively). A plot of the distributions of fixations at the factor levels for symmetry type and fill as size increases showed that an interaction with fill was only noticeable in the large size condition.

Eye movement strategies. Capturing eye movements in the symmetry judgment task allows us to test whether qualitative differences guided specific fixations in visual search. To see if subjects looked more at quantitative differences than qualitative differences, we classified each vertex in each asymmetric stimulus as matching (being part of a symmetric feature), quantitative mismatch (being part of a quantitative difference), qualitative mismatch (being part of a qualitative difference), or on axis. We than assigned each sample to its closest vertex. Since there were four times as many symmetric vertexes as asymmetric vertexes, we scaled the symmetric sample counts accordingly.

The results showed longer looking times for quantitative differences than qualitative differences (Figure 6). A one-way ANOVA confirmed that the distribution of quantitative mismatch samples is significantly higher from qualitative

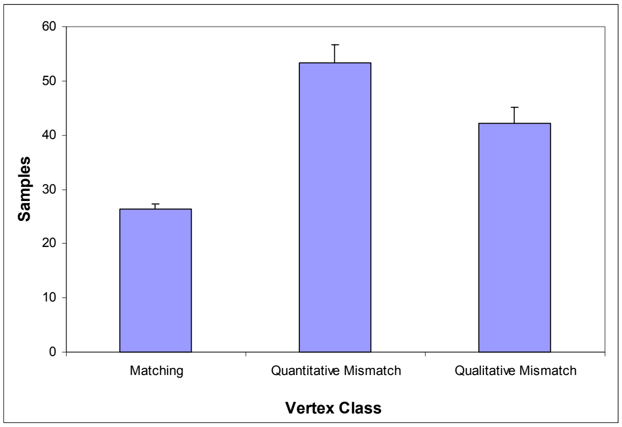

Figure 6 Differences of distributions of samples on types of features in stimuli

mismatch samples ($F(1,46)=26.30$, $p<0.001$).

Lateral Bias Effect. The experiment by Locher & Nodine (1973) asked subjects to rate the complexity of presented stimuli that varied in symmetric quality as well as the number of sides (complexity). Using eye-tracking data, Locher & Nodine reported 11 out of 16 symmetric trials showed a bias of fixations of at least 70/30 to one side of the stimulus relative to the symmetric axis. For asymmetric figures, they reported 14 of 16 shapes showed a distribution of 50/50 or 60/40 between top and bottom axis (asymmetric figures were bisected in the horizontal axis). These results indicate a lateral bias effect for symmetric but not asymmetric figures. By calculating fixation bias over the three symmetry types in this experiment, we can test whether the lateral bias effect extends to near-symmetric figures with qualitative or quantitative differences even though they are both asymmetric in exact terms.

If we compare the mean bias ratios of stimuli in the levels of the conditions, we notice bias values reported by Locher and Nodine in most conditions. A one-way ANOVA test showed no significance in the difference of distributions based on symmetric quality (see Figure 7). This result extends the initial claim made by Locher and Nodine: near-symmetric figures show the same bias as symmetric figures.

To compare our result with the Locher and Nodine analysis, we analyzed fixations in asymmetric figures according to the horizontal axis. In this case, mean ratios were at least 0.70 in all factor levels. This indicates that our asymmetric shapes are more similar to symmetric shapes than the Locher and Nodine asymmetric stimuli. In order to obtain a clearer picture of the nature of the bias, we analyzed a window of samples (Figure 8). The window analysis indicates that the bias exists early in processing, and decreases over time. Lateral bias also decreases as size increases.

Continuous Symmetry Measure. One prevalent model that has been shown to predict subject performance in symmetry judgments has been the Continuous Symmetry Measure (CSM) (Zabrodsky, Peleg, & Avnir, 1992). Using a weighted sum of squared radial differences, CSM measures a figure's difference to the figure with a symmetric exemplar shape. In our stimulus set, figures that are asymmetric (quantitative or qualitative differences) are asymmetric in one feature. The closest symmetric shape (minimum CSM) is the minimum CSM of two potential figures: one setting the asymmetric feature to match the corresponding feature or vice-versa. We calculated CSM for each of the asymmetric stimuli. A one-way ANOVA showed significance in the difference between the two distributions ($F(1,94)=7.46$ $p<0.01$).

We compared CSM with mean accuracy for asymmetric trials (quantitative and qualitative). A Pearson correlation test showed that CSM was not correlated to accuracy in the stimulus set (r=0.059, *ns*). Correlation tests based on levels of size showed no significance: size small, (r=0.101, *ns*) for size medium (r=-0.076, *ns*), for size large (r=-0.156, *ns*). Correlation tests based on levels of fill did show significance for unfilled shapes (r=0.289, p<0.049). A correlation test for each level of size and symmetry quality showed the only a marginally significant correlation between CSM and accuracy for figures with qualitative differences and small size (r=-0.497, p<0.05). These results suggest that our earlier results for qualitative differences are not a side effect of CSM.

General Discussion

These results support the findings of symmetry processing found in (Ferguson et al., In preparation): participants judged near-symmetric figures more accurately when they contained qualitative rather than quantitative differences. This replicates the result of the earlier experiment across two fill and three size conditions. This experiment also shows that qualitative and quantitative differences affect the pattern of visual search. In general, participants looked longer at figures with quantitative rather than qualitative differences, and also fixated on them more. In addition, participants were more likely to fixate on any individual vertex when it was part of a quantitative difference than

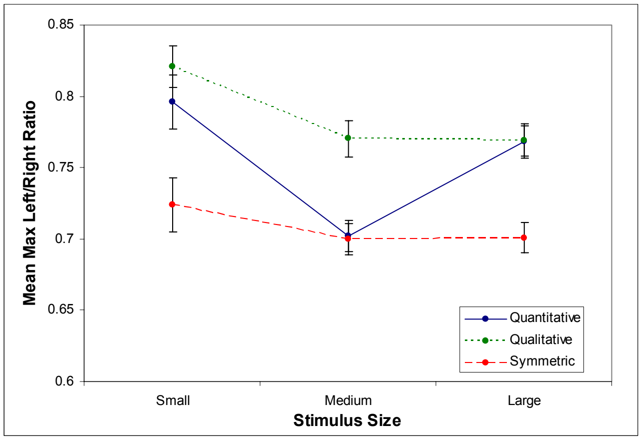

Figure 7 Mean max left/right ratio for bias in symmetry axis

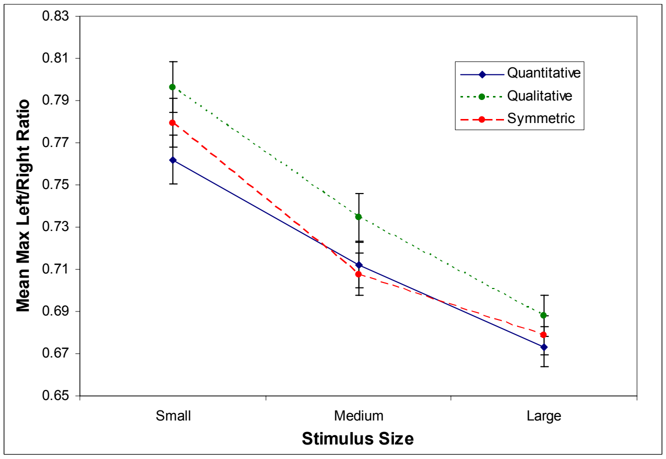

Figure 8 Left/right ratio using 200 sample window

when it was part of a qualitative difference. All of these factors support the assertion that the visual system is significantly more sensitive to visual differences in near-symmetric figures when those differences are qualitative and involve a relational difference, rather than a difference of degree.

Speed vs. Accuracy. These results show that the effect for qualitative differences is not due to a speed/accuracy tradeoff. At the same time, accuracy is worst in figures with quantitative differences. In contrast, figures with qualitative differences require the least time to analyze and subjects are quite accurate to judge symmetry. For all figures, lowering response times do not affect accuracy, indicating that there is not a speed/accuracy tradeoff.

Conclusion. The results presented here provide further evidence that in a two-stage process model of symmetry perception, qualitative features are handled in the early stage consistent with an alignment-based process.

Future Work

In future work, we expect to conduct further experiments aimed at refining these results. An important follow-on to this experiment will add a control over stimulus presentation time. By using an increasing discrete stimulus presentation time, we hope to eliminate the variance created by experimenter-based advancement of stimuli, while still capturing the salient eye movements. Another important follow-on experiment will be to capture early symmetry detection with better temporal resolution using electroencephalographic (EEG) recordings.

Acknowledgments

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