The Role of Symmetry in the Recognition of Faces at Novel Orientations

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Abstract

Bilaterally-symmetric objects such as faces are easily recognized from an orientation that is symmetric with respect to the original view. Several authors have proposed that a simple image-based transformation can account for this effect. In four experiments we test this model and show that it is only one representation that is used. We demonstrate that by itself the image-based model is insufficient to account for the recognition of inverted and tilted faces, faces with luminance asymmetries, or data from memory experiments where faces are studied in a smooth motion sequence. The results bear on the nature of the representations that are used to recognize faces at symmetric orientations, and show that they are not limited to transformations applied to 2-dimensional image-based representations. Extensions to other domains beyond symmetric orientation recognition are explored.

A major conclusion in the field of object recognition is that objects within a class tend to be recognized at novel orientations in a viewpoint dependent manner: Objects are easy to recognize at or near a studied view, and performance degrades progressively for novel views that deviate from the studied view (e.g. Rock & DiVita, 1987; Tarr & Pinker, 1989; 1990; Bülthoff & Edelman, 1992). An important exception to these results is the recognition of bilaterally symmetric objects at symmetric orientations. As long as the axis of symmetry within the object is vertical and the object is rotated around the vertical axis, the symmetric orientation view produces an image that tends to appear similar to the mirror image of the original view. Several authors have demonstrated that this view supports good recognition performance (Vetter, Poggio & Bülthoff, 1994; Liu, et al., 1995). For example, using a same-different task, Troje and Bülthoff (1998) show that when a face is studied at a 45° orientation, recognition at the symmetric orientation (-45°) is almost as good as the 45° orientation, and much better than at the frontal (0°) orientation.

The recognition of faces and objects at symmetric orientations is an important phenomenon from several standpoints. First, this facility may be tied to the detection of bilateral symmetry within a single objects. Several authors (e.g. Watson & Thornhill, 1994) have pointed out that symmetry may be a measure of genetic fitness. However, the salience of such symmetry disappears rapidly as the face is rotated away from the frontal view. The same mechanism that supports symmetric orientation recognition may also be used to evaluate bilateral symmetry at views other than the frontal view. Second, part of the ability to recognize the symmetric orientation view may be built in to the earlier stages of visual processing. For example, Logothetis (1998) found cells in area IT that strongly responded to both left- and right-facing views of a face, but not to frontal views.

What sort of transformation of the studied image would support this strong symmetric orientation recognition performance? Prior research on the recognition of faces at symmetric orientations suggests that the processes that mediate recognition of the symmetric view rely on properties closely related to the studied image of an object. For example, Troje and Bülhoff (1998) compared a mirror symmetric image (formed by flipping the studied image

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horizontally) with a symmetric-orientation view. Recognition of both images was nearly as good as that of the original view, which demonstrates that both the symmetric-orientation and mirror-image views are in many ways equivalent to the original view when used to probe memory. However, the ability of the perceptual system to use information in the symmetric orientation view is very dependent upon the surface features of the image: when the face was lit by a light source that is off the midline axis, the symmetric orientation view appears quite different from the original view, and recognition performance in the experiment suffered as well. Thus there was little evidence that observers extracted 3-dimensional shape information that would allow them to compensate for changes in the location of the illuminant.

Based on these findings, Troje and Bülthoff (1998) conclude that the processes that recognize the symmetric orientation on the basis of the studied view are mainly image-based, and do not extract the structural information or higher-order features that would make perception robust across changes in illumination. Because of this dependence on the raw image information such as reflectance information, Troje & Bülthoff (1998) suggest that recognition of the symmetric viewpoint can be accomplished by performing two-dimensional image transformations, and that no abstraction of three-dimensional information or higher-order features (what they term 'scene attributes') was required. This view was summarized by Troje (1998): "Subjects do not generalize to new instances of scene-attributes. They compare images."

A specific model of two-dimensional image transformations has been proposed by Vetter, Poggio and Bülthoff (1994) and Vetter and Poggio (1994), who demonstrate that recognition of bilaterally-symmetric objects at a symmetric orientation could be subserved by a mechanism that reflects the landmarks of a two-dimensional view across the vertical axis in a pure image-plane operation. This requires no knowledge of the three-dimensional structure of the object, just an image-based transformation that could, in principle, be handled by fairly low-level perceptual mechanisms. In addition, the transformation treats the entire image as a single entity, performing what amounts to a template match of the flipped original image onto the symmetric orientation view.

Two Models of Recognition

The two different sources of information tested by Troje & Bülthoff (1998) are similar in several respects to two general classes of models that have been proposed in the object and face recognition literature. Identification of faces is thought to rely on configural or holistic representations, which generally is taken to imply that the interrelationships among the features is important, or that the locations of individual features are compared to a single reference point. Cooper & Wojan (2000) refer to this as coding by coordinate relations because of the emphasis on each primitive feature being located in its original location for a good match to previous examples. All metric information is saved with respect to the feature locations, but very little abstraction is applied to this metric information. Because the information is saved in relatively raw form, this representation may be thought of as storage expensive but computationally inexpensive.

The identification of objects is thought to rely more on featural representations, in which only the categorical relations among primitive features are important. Thus an object is described by its features as well as relative directional descriptors for these features such as above, below and beside. The representation does not maintain the exact coordinates of the primitive features. Cooper & Wojan (2000) refer to this as coding by categorical relation.

Of these two models, the image-based representation proposed by Troje & Bülthoff (1998) to account for symmetric orientation recognition corresponds most closely with the coordinate relations model, since the two-dimensional image-based representation preserves the metric information of the feature locations. In the present article we consider an alternative class of models that places less emphasis on the exact locations of the features and more on their identity and relative positions, and may include a different set of primitive features. Thus the scene-based representation which extracts 3D structure in order to express bilateral symmetry even in the case of asymmetric illumination is one instance of a categorical relations model, since higher-level features are extracted and compared with less regard to their precise locations.
The image-based representation has several drawbacks. First, it requires a great deal of storage, although this may not be an issue for humans, especially for short durations. Second, the image-based representation tends to have difficulty with transformations of the original image such as rotation, scaling or translation, unless some form of rectification is performed on the image. Finally, Hummel & Stankiewicz (1996) point out that such models are most useful for within-category distinctions such as face identification. Metric information is relatively useless when identifying an object as a chair or a cup because the instances are so variable. However, image-based models involve less abstraction and therefore less processing of the input, and so observers may rely on such a representation when it is well-suited to the task.

The present studies address the degree to which the image-based (coordinate relations) representation can account for recognition of the symmetric orientation view and whether alternative representations are also used, such as one based on an analysis of primitive features and their categorical relations. We should stress that our goal is to establish the extent to which information other than an image-based representation is used, and thus we use a variety of different paradigms and stimuli in an attempt to determine whether additional representations beyond the image-based transformations are at work. In Experiments 1 and 2 we address the role of coordinate (image-based) and categorical relations models in a perceptual matching task. In Experiment 3 we demonstrate evidence for symmetric orientation recognition in a memory paradigm, and illustrate the robustness of the phenomenon, suggesting less reliance on image-based representations that that found in perceptual matching tasks. Finally, in Experiment 4 we demonstrate that placing a study image in motion improves recognition at the symmetric orientation, suggesting that observers had abstracted 3-dimensional structural information that improves recognition at the symmetric orientation.

Note that in many cases we are intentionally vague about the nature of the alternative representation that might work in addition to an image-based coordinate representational system. The goal of the experiments are to first establish the need for this alternative representation (and therefore the single image-based representation takes on the role of the null hypothesis) and then to determine the properties of this additional system. Consider an analogy from computer graphics. An image-based system may be thought of as a Photoshop image, which contains only two dimensional information with no abstraction. Adding additional information such as resizable object handles like those found in drawing programs like Canvas would provide one level of abstraction. Other programs such as three-dimensional rendering programs would preserve 3D structure of objects, and provide another level of abstraction from the 2D image. Each of these are possible representations, and the current experiments are designed to see if the image-based system alone is sufficient, and if not, what other representations might also be at work.

**Experiment 1**

Cooper and Wojan (2000) tested the coordinate and categorical relations models using an elegant and straightforward image manipulation that involves raising one or both of the eyes of a face. Here we adopt their method and gratefully acknowledge their influence on our work. Examples of their manipulation applied to our stimuli are show in Figure 1. The observer studies a face with neither eye raised (left panel of Figure 1) and is then asked to recognize the same face with either one or both eyes raised. The critical distinction between categorical and coordinate relations models is that a system based on coordinate relations prefers to have every feature in its original location. A categorical relations model can tolerate some error in the absolute locations of features as long as the important categorical relations are preserved. Thus the categorical relations model predicts better performance with both eyes raised, while the coordinate relations model predicts better performance in the one-eye raised stimulus.

Cooper and Wojan (2000) used this technique to illustrate that face recognition relies on coordinate relations while face/non-face classification relies on categorical relations. They found better recognition with the one-eye raised condition, but better classification (into face/non-face categorizes) with the two-eye raised condition.
In Experiment 1 we use similar logic to test the proposition that the symmetric orientation view is recognized using an image-based representation that preserves the coordinate relations. Observers studied a face at a 25° orientation with neither eye raised. They were then asked to recognize the face at the -25° orientation1. This test face could be either have neither eye raised, one eye raised, or both eyes raised. Distractor faces were included on half of the trials, and they could have either zero, one or both eyes raised as well.

If the image-based representation proposed by Troje & Bülthoff (1998) does indeed subserve recognition at the symmetric viewpoint, then performance in the one-eye raised condition should exceed that of the two-eyes raised condition. Given that Cooper and Wojan (2000) found evidence for an image-based type representation for face recognition, we might expect a similar model to work for symmetric orientation recognition. However, there are conditions under which faces tend not to be recognized using a coordinate relations representation. When faces are inverted, observers typically rely on individual features rather than the features in context with their relations. Perhaps the best example of this is by Tanaka & Sengco (1997), who showed that the recognition of individual features from inverted houses and faces was not sensitive to their configuration. However, features from upright faces were better recognized in the context of a face rather than in isolation. In addition, recognition of the mouth feature was influenced by the inter-eye spacing, demonstrating the importance of metric spatial distances in face processing. Configuration had no effect on any feature in the inverted faces. Thus only upright faces appear to depend upon the metric relations that a coordinate representation preserves.

To test the generality of the image-based representation proposed by Troje & Bülthoff (1998), we inverted all faces for half of our observers. If observers now rely less on a coordinate relations representation and more on individual features and their categorical relations, we would expect the deficit for the both-eyes condition to disappear or even reverse.

To summarize the critical conditions, we tested observers at the symmetric orientation with a face that had either neither, one or both eyes raised. Half of the observers saw all images inverted. If observers rely on an image-based or coordinate relations representation, we expect better performance in the one-eye raised condition compared with the two-eyes raised condition at the symmetric orientation view. However, observers may instead rely on an alternative representation that does not preserve metric relations but involves a comparison of individual features or their categorical relations. In this latter case we expect better performance in the two-eyes raised condition rather than the one-eye raised condition, because we preserve the important categorical relations (i.e. the eyes are even with each other).

Method

Observers

The observers were Indiana University undergraduate students. There were 51 observers in the upright face portion of the experiment, and 49 observers in the inverted face portion of the experiment. Observers saw either only upright faces or only inverted faces. The observers received course credit for their participation.

Stimuli

The stimuli were 16 laser scan models of human heads obtained from a Cyberware(TM) laser scanner. During scanning, the heads of the scanned faces were covered with a beige cap that hid most of the hair. The laser scanner produces a depth map of the head, mapping the deformations of the face from a cylinder at 512 (horizontal) by 256 (vertical) positions. Red, green and blue color values are also measured at each point.

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We had no control over the scanning procedures, and we observed slight asymmetries in both the texture and structure of the heads. The structural asymmetries came about from the natural variations in the human head, but the slight texture asymmetries came from asymmetric lighting during the scanning process. This produced a texture asymmetry that will rotated with the face (as opposed to the asymmetric lighting of Troje & Bülthoff (1998) which did

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1 A 25° angle was used rather than the 45° angle used in other work because we did not want our raised eye to be occluded by the rest of the face as it rotated away from the frontal view.
not rotate as the face rotated). We did not want these asymmetries interacting with the asymmetries introduce by the one-eye-raised condition, and thus we removed both the texture and structural asymmetries as described below. Note that we evaluate the effects of symmetrization on recognition at the symmetric angle in Experiment 2, and use unsymmetrized faces in Experiments 3 and 4.

The heads were symmetrized and the eye movement manipulation was performed as follows. First, the depth map (which provides the three-dimensional structure of the head) and the corresponding luminance map were treated as 512 pixel by 256 pixel images. In the depth map, the value at each location provides the deformation from a cylinder that gives the face its structure. The corresponding pixel in the luminance map provides the color at that location once the depth map has been molded to fit the depth map. We then used graphics programs to flip both texture and depth maps horizontally which creates what might be thought of as the mirror face. We then placed control points on the important features of both of the texture maps. Then, using morphing procedures (Beier & Neely, 1992) we combined the original face with the mirror face by warping the locations of the features onto an average set of locations (computed individually for each faced) and then performing a cross-fade blend that combined the two images. The resulting face looks quite realistic, and results in a completely symmetric face at both the level of the structure and the texture. We noted a slight blurring effect in the texture as a result of the blending process, so we introduced a slight sharpening effect in the texture maps prior to 3D rendering of the head models.

Once we obtained the symmetrized face, we took advantage of the fact that our program put out the control points for the averaged features. To raise an eye, we merely moved the target positions for the control points of one eye (and eyebrow) upward and warped the texture and depth maps to produce a new image. This procedure was repeated three times for each of the 16 heads to produce models in which the left eye, right eye, or both eyes were raised.

The models were then converted into files that could be photo-realistically rendered in the POV-Ray rendering package. These were rendered using a light source positioned above and behind the location of the virtual camera. The heads were rotated around the vertical axis, which extends through the middle of each head.

The stimuli were presented in full color on two 21” monitors that mirrored the monitor of a Macintosh 7200 PowerMac computer. Timing and stimulus control was provided by the VideoToolbox library of c routines (Pelli & Zhang, 1991). Data collection was provided by a two-button keypad with millisecond resolution.

**Design and Procedure**

The stimuli were presented in a sequential same-different task. A study face appeared for 1440 ms and was replaced by a pattern mask composed of parts of various faces. This mask remained on the screen for 1000 ms, and then was replaced by a test face. The study face was positioned slightly to the left of the center of the monitor, and the test face was positioned slightly to the right of center. The test face remained on the screen until all subjects had responded.

The test face was the study face at some orientation (and perhaps with one or more eyes raised) on half of the trials, and a distractor face, chosen from the remaining 15, was presented on the remaining trials. All variables were counterbalanced, such that the study face appeared either at an orientation of 25° or -25°. At test it appeared at 25°, 0° or -25°. Observers were given instructions that they should respond same if the same person appeared at test they should push the 'same' button, even if the person appeared at a new orientation or had one or more eyes raised. They were given practice trials and feedback to insure that they understood the instructions. Observers were also asked to respond as quickly as possible, maintaining a high degree of accuracy. We gave them feedback via a flashing LED if their response exceeded 800 ms on any particular trial.

Subjects completed 240 trials, which lasted approximately 45 minutes.

**Results**

We did not observe differences in the results depending on whether the study face was oriented to the left or the right, and so we collapsed over the two study angles. We also did not observe differences between left or right
eyes raised, and so we combined these into a single one-eye-raised condition.

Figure 2 summarizes the correct recognition (hit rate) results for the upright heads. There were no main effects and no interactions (all p’s>0.05) in the false alarm rates. In addition the pattern of reaction times tended to follow that of the hit-rate data and do not show evidence of speed-accuracy tradeoffs. Thus we restrict our analyses to the hit rates and discuss specific reaction time comparisons as necessary.

In Figure 2 only the no-eyes-raised frontal view condition is shown for comparison with the original and symmetric angle conditions. Here we replicate previous work by Troje & Bülthoff (1998) by showing a substantial advantage of the symmetric angle over the frontal view, which is the basis for the symmetric orientation effect.

The comparison of most interest is that between the one-eye-raised and both-eyes-raised conditions. Recall that the image-based representation predicts better performance for the one-eye raised condition at the symmetric orientation, and this is exactly what we observe \(t(50)=2.694, p<0.01\). An analysis of variance excluding the frontal views reveals an interaction between the eye move manipulation and test angle (original vs. symmetric angle) \(F(2,100)=5.08, p<0.01\). We attribute this interaction to the relative immunity to the eye raise manipulation at the original test angle. Thus whatever representation is used to recognize the symmetric angle view seems to be more affected by raising eyes than that used to recognize the original view.

A different pattern of results emerges for the inverted faces, as shown in Figure 3. There is no longer an interaction between test angle and the eye move manipulation \(F(2, 96)=1.2, \text{n.s.}\). More importantly, the deficit between the one-eye raised and both eyes raised conditions seen at the symmetric orientation is eliminated and nearly reverses. At the symmetric orientation, performance in the both-eyes raised condition almost exceeds that of the one-eye raised condition \(t(48)=-2.005, p=0.051, \text{two-tailed}\). This interaction between inversion and the number of eyes raised (zero, 1 or 2) was confirmed by a between-subjects comparison ANOVA, and was significant \(F(2,196)=4.5, p<0.05\). This illustrates that the eye move manipulation affects performance differently for upright and inverted faces.

**Discussion**

The critical comparison for distinguishing between the image-based and alternative representations is performance in the one-eye and both-eye raised conditions at the symmetric orientation. For upright faces, performance was better in the one-eye raised condition than the both-eye raised condition. This was true for both the original orientation and symmetric orientation conditions, indicating that observers rely on coordinate-based information for both original orientation and symmetric orientation recognition. This trend disappeared and nearly reversed with the inverted faces, suggesting that the image-based representation is limited to recognition of upright faces. The significant interaction between the number of eyes raised and whether the face was upright or inverted demonstrates that the importance of coordinate and categorical relations for recognition at the symmetric orientations changes depending on whether the face is upright or inverted.

Vetter, Poggio & Bülthoff (1994) have proposed that symmetric orientation recognition of any bilaterally symmetric object is subserved by an image-based transformation that relies on coordinate relations. The data from the inverted faces suggests that such a representation is only used at the symmetric orientation when the original image codes for coordinate relations. In the case of inverted faces and perhaps basic-level object recognition tasks, only categorical or feature-based representations may be preserved, limiting the utility of the image-based transformation proposed by Vetter et al. (1994) and Troje & Bülthoff (1998).

**Experiment 2**

The results of Experiment 1 support the proposition that image-based transformations that preserve coordinate relations are used to recognize faces, but that such a process is limited to upright faces. In the face recognition literature, inverted faces are thought to be recognized on the basis of a model that does not preserve coordinate relations (e.g. Tanaka & Sengco, 1997). Given that such a representation is also used to recognize inverted faces at the symmetric orientation, it may appear that the symmetric orientation view is recognized using
the same representation as that used to recognize the original orientation view.

In Experiment 2 we ask whether a representation other than an image-based, coordinate relations representation might also contribute to the recognition of upright faces. To address this, we devised two manipulations that we thought would disrupt an image-based template match system and encourage observers to rely on an alternative representation if one exists.

Our first manipulation involved introducing a 30° tilt applied in the image plane after rotation. Unless a rectification procedure is first applied to an image, a template match system will have difficulty matching a tilted image to the original. We reasoned that under these circumstances the alternative representation (if it exists) would be more likely to play a larger role in the recognition process, and therefore reveal some of its properties. Note that we consider a 30° tilt to be enough to disrupt an easy match of an image-based representation, but not so tilted that the face changes its properties. In the face processing literature, inverted faces are often described as having properties more like objects and less like faces (Tanaka & Sengco, 1997), but we consider a face tilted at 30° to still be processed as a face.

Our second manipulation was motivated in part by the asymmetric illumination condition of Troje & Bülthoff (1998). They found that asymmetric illumination drastically reduced recognition of the symmetric orientation view. We noted that our original unsymmetrized images contained asymmetries, especially in the texture maps but also in the structure of the head. The texture differences were introduced by asymmetric lighting of the individual during the scanning procedure, which we had no control over. Both the texture and structural asymmetries were removed by the symmetrization procedure described in Experiment 1, but in light of the effects of asymmetric lighting reported by Troje & Bülthoff (1998), we include both symmetrized and unsymmetrized faces in Experiment 2.

Based on the results of Troje & Bülthoff (1998), we expect better symmetric orientation recognition with the symmetrized faces. However, we are most interested in interactions between symmetrization, test angle and tilt. Figure 4 shows examples of our stimuli and provides the logic by which we expect an interaction between independent variables. Assume for the moment that observers have access to two different types of representations: an image-based representation and one in which more abstract feature elements or perhaps categorical relations are the basis for comparison. When the test face shown at the symmetric orientation is not tilted, observers tend to rely on an image-based comparison because this requires little abstraction and therefore presumably less mental effort. The large storage requirements necessary to maintain such a representation are not an issue because the task requires relatively little long-term storage and therefore might be accomplished by massively parallel lower-level visual mechanisms.

In the case of unsymmetrized faces as shown on the left side of Figure 4, a reliance on the image-based representation leads to poor recognition performance because of the texture asymmetries. However, when the test image is tilted, we suggest that observers tend not to use an image-based representation and instead rely on information such as abstractions derived from individual features or representations in which only categorical relations play a role. With unsymmetrized faces, however, this turns out to be a good strategy, because by relying less on image-based information and more on individual features or abstractions, the observer tends to overcome the asymmetries in the texture. While an image-based comparison would return the incorrect answer, a representation that relies on more abstractions will be robust against texture or structural asymmetries. Thus, as shown in the left side of Figure 4, we predict that the performance degradation going from the original to the symmetric angle should be smaller for tilted faces. In fact, depending upon the absolute levels of recognition performance at the original angle, we may observe a surprising inversion such that faces at the symmetric orientation should be better recognized when tilted than when not tilted.

Note that this logic only applies to unsymmetrized faces. As shown on the right panel of Figure 4, using an image-based representation with a symmetrized face should work just fine for the untilted, symmetric orientation face because there are no texture differences to disrupt the image-based representation.

Because the use of an image-based representation produces an incorrect response only
for untilted, unsymmetrized faces at the symmetric orientation, we expect a three-way interaction between tilt, test angle (original or symmetric angle) and symmetrization of the face. Another way of thinking about this prediction is that the interaction between test angle and tilt depends on the level of symmetrization.

To summarize the predictions of the various models, we predict that, in general, tilting a test image will inhibit an image-based comparison system, causing a (perhaps slight) reduction in recognition performance at the original orientation view. However, the difference between original orientation view and symmetric orientation view performance will be smaller for tilted faces. Depending upon absolute levels of performance for tilted faces, we may find that performance at the symmetric orientation view is better for the tilted face compared with the untilted face. This result holds only for unsymmetrized faces, because the image-based system works well for the symmetric orientation view for symmetrized faces.

**Method**

**Observers**

The observers were Indiana University undergraduate students. There were 20 observers in Experiment 2. The observers received course credit for their participation. Note that although we used fewer observers in Experiment 2, each ran twice as many trials as those in Experiment 1.

**Stimuli**

The stimuli for Experiment 2 included the 16 head models from Experiment 1, to which we added the 16 unsymmetrized (original) head models. Thus each face had an unsymmetrized and a symmetrized version. As noted above, the symmetrization procedure tended to slightly blur aspects of the texture, and of course the symmetrized faces looked more symmetric. In order to prevent subjects from using these artifacts as cues to the correct answer in the same/different task, we chose distractors from the same class of faces. Thus if an unsymmetrized face was used as the study face, the distractor test face would also be an unsymmetrized face.

**Results**

Figure 5 shows the hit rates for all conditions, with the frontal view conditions combined together to provide a comparison for the symmetric orientation view performance. As with Experiment 1, there were no main effects and no interactions (all p’s>0.05) in the false alarm rates, and thus we restrict our analyses to the hit rates. In addition, we found no differences between faces studied at 40° and -40°, and thus we average over these conditions.

The left side of Figure 5 presents the data from unsymmetrized faces. The logic described in Figure 4 suggested that the difference between original and symmetric orientation views would be smaller for tilted faces. This is indeed the case. Surprisingly, we find that performance at the symmetric orientation is higher in the tilted condition than the untilted condition. This result is counterintuitive, because one would expect that tilt would only decrease recognition performance.

One issue that arises with the comparison above is the possibility of a speed-accuracy tradeoff. In this particular situation, there is no speed-accuracy tradeoff, because the reaction times in the two conditions described above are virtually identical: the median reaction time for correct responses is 583 ms for untilted and 584 ms for tilted faces.

The right side of Figure 5 shows the results from the symmetrized faces. Performance at the symmetric orientation is high in both untilted and tilted conditions, with tilt extracting a small performance decrement. This represents a completely different ordering of the symmetric orientation views than with the unsymmetrized faces.

The dramatic change in the pattern of the data between unsymmetrized and symmetrized faces leads to a significant three-way interaction.
between test angle (original or symmetric angle), tilt, and symmetrization (F(1,19)=8.73, p<0.01). This result is consistent with the logic described in Figure 4 that proposed that tilt would disrupt the image-based comparison system, but in the case of unsymmetrized faces with texture asymmetries this would actually prove beneficial. Some readers may feel comfortable interpreting a three-way interaction only if the two-way interactions are significant, and thus we report these F-values here: Test angle x tilt (F(1,19)=11.1, p<0.05), test angle x symmetry (F(1,19)=52.14, p<0.05) and symmetry x tilt (F(1,19)=4.86, p<0.05).

Discussion
The results conform to the predictions of Figure 4. Unsymmetrized faces do indeed show improved performance at the symmetric orientation when tilted. This result is not true for symmetrized faces, and the three-way interaction between test angle, tilt and symmetrization is significant.

These data are not consistent with an image-based representation even if one were to include a rectification system for the tilted faces. The image-based representation with a rectification system would produce performance in the tilted condition that is equivalent to the untilted condition, but could not place the tilted performance above the untilted condition at the symmetric orientation as is found in the data with unsymmetrized faces.

Our interpretation of this data is that when viewing a tilted test face observers reject an image-based comparison in favor of one that is more flexible, involves more abstractions, and is less reliant on surface texture or luminance asymmetries.

The results confirm, using different variables and methods, the results of Experiment 1 that demonstrate that while an image-based representation is used for recognizing faces at the symmetric orientation, additional representations do contribute and are capable (in some cases more so) of providing recognition of the symmetric orientation view. We conclude that the range over which an image-based system is used is somewhat limited: observers tend to rely on it for its computational ease when conditions appear to allow it (i.e. short storage period, upright faces) but are prepared to abandon it for a representation that includes more abstractions and is more robust against changes in surface properties such as luminance or tilt.

Symmetric Orientation Recognition In Memory
The existence of a second form of representation that works in addition to an image-based representation suggests a level of abstraction by the visual system. The purpose of this abstraction would be to create a representation that is works with a wider class of faces for which an image-based approach is not well suited, such as objects or inverted faces. In addition, such a representation would be more robust against texture or structural asymmetries. Given the large storage requirements mandated by an image-based representation, it seems likely that for longer-term memory tasks more abstraction (and therefore a form of compression) would take place. To address the nature of these abstractions that enable recognition at the symmetric orientation for longer-term recognition, we conducted two memory experiments. Our first memory study (Experiment 3) establishes the symmetric orientation effects in memory and addresses whether observers differentiate between the original and symmetric views. The second memory study (Experiment 4) explores whether observers can use motion to improve recognition at the symmetric orientation, perhaps by extracting some three-dimensional information or using motion to extract a representation that is not tied to texture or structural asymmetries.

The memory experiments use manipulations (motion and cognitive control) that differ somewhat from those used in the perceptual matching tasks (e.g. eye shifts, symmetrization and tilt). We felt that the nature of the representations that support recognition memory might be less influenced by variables such as tilt, and thus we chose manipulations that we deemed more likely to have longer-term effects. Although this does not allow a direct comparison between perceptual matching and recognition memory, the experiments do provide additional evidence on the nature of the representations that go beyond an image-based transformation.

Experiment 3
We have two goals in Experiment 3. First, to our knowledge the symmetric orientation ef-
effects have not been established in recognition memory, despite the general agreement that the results of perceptual matching tasks should be extended to memory (see Troje & Bültzoff, 1998).

Second, if we do find symmetric orientation effects, can the observer discriminate between the original view and the symmetric orientation view? Intuitively, one may think this trivial. However, in longer-term memory the directionality of the face may be poorly encoded as a result of the fact that orientation is usually irrelevant for identification. For example, in a classic memory demonstration, Nickerson & Adams (1979) produced drawings of pennies that included versions with Lincoln's face reversed. Fewer than half of the observers could pick the correct penny out of the 15 examples. In the neuropsychological literature, Turnbull & McCarthy (1996) describe a patient who could not discriminate between an object and its mirror image while both were clearly visible. The results suggest that orientation information is fragile or possibly stored in a location that can be damaged, while leaving object recognition intact. Finally, Price & Gilden (2000) demonstrate that when observers are asked to remember a rotating, translating object, the observers decouple the two events and retained only the translation direction. The translation direction tends to be more informative because it indicates an object that may require interaction or uniquely identifies the object because two objects typically cannot occupy the same location simultaneously. Rotation direction may not require an adaptive behavior because any particular state of the object can be achieved by either clockwise or counterclockwise rotation. Thus rotation direction is relatively uninformative and observers apparently do not encode it. Similarly in the present experiments, the orientation (left- or right-facing) of the face is usually irrelevant for identification purposes, since faces can be observed from either orientation. Thus we may observe a similar dissociation between identity and orientation in face recognition.

To assess whether observers could distinguish between representations of the original and symmetric orientation view, we conducted Experiment 3 as a between-subjects design. Half of the observers were asked to say 'old' only if the face appeared at its original orientation. The other observers were asked to say 'old' only if the face appeared at its original orientation. We term these instructions Inclusion and Exclusion, respectively.

We use an old/new recognition paradigm in which observers studied 12 faces. Each of these is studied in one of 5 possible study orientations, which were 70°, 40°, 10°, -20° and -50°. They were then tested with all 5 orientations, as well as with 12 distractor faces also shown at all 5 orientations.

We are interested in whether symmetric orientations are better recognized than other novel orientations, but we chose study and test angles that were asymmetric around the frontal view. Our rational for this choice was as follows. Previous evidence for good recognition at symmetric orientations suggests that this involves a fairly low-level comparison of the 2D image information. However, Experiments 1 and 2 demonstrated that other representations were also at work. We are looking for evidence that higher-level information is used, but we did not want our observers to be able to exploit the fact that exact mirror-symmetric angles were included in the test session. Thus by using images that were rotated away from the symmetric view by at least 10 degrees we could assess the robustness of symmetric orientation recognition effects without the data becoming contaminated by observers using a strategy that exploited the exact match between a studied view and its symmetric test view. Finding evidence for symmetric orientation effects even under these conditions would illustrate the strength of this phenomenon. In addition, to provide further evidence of the strength of the phenomenon, we used unsymmetrized faces in Experiments 3 and 4.

Method

Observers

There were 167 Indiana University students in the Inclusion task and 140 students in the Exclusion task. They received course credit for their participation.

Stimuli

The stimuli were 24 head models, which included the 16 unsymmetrized heads from Experiment 2 plus an additional 8 head models that shared similar characteristics.
As with the previous studies, the models were converted into files that could be photo-realistically rendered in the POV-Ray rendering package. These were rendered using a light source positioned above and behind the location of the virtual camera. The heads were rotated around the vertical axis, which extends through the middle of each head. The study orientations were 70°, 40°, 10°, -20° and -50°. The same orientations were used at test.

The stimuli were presented in full color on two 21” monitors that mirrored the monitor of a Macintosh 7200 PowerMac computer. Timing and stimulus control was provided by the VideoToolbox library of c routines (Pelli & Zhang, 1991). Data collection was provided by a Macintosh Centris 610 computer with 6 external keypads. Up to 6 observers participated at one time.

Design and Procedure

Twelve faces were chosen as target faces for the entire experiment, and 12 were reserved as distractors. Each of the 12 faces was randomly assigned to one of 5 study orientations, which was rotated across groups so that each face appeared at each study orientation an approximately equal number of times. The faces were shown for 2 seconds, and were separated by 2 seconds. Following the presentation of the study faces, the observers were shown 120 test trials, which consisted of 60 target faces (12 targets at all 5 orientations) and 60 distractor faces. Those observers in the Inclusion condition were told to respond ‘old’ if a studied face appeared at any orientation. Those observers in the Exclusion condition were told to respond ‘old’ only at the identical orientation. In order to prevent observers in the Exclusion condition from explicitly encoding the orientation, the response instructions were provided only after the conclusion of the study portion of the experiment.

Prior to the study session, observers were given a brief practice session in which they viewed 3 practice faces at various orientations. These faces were not included in the later study or test session. Prior to the test session, the observers were given 6 practice test trials. In particular, observers were shown two test trials early in the practice test session, one that had an old face at its original orientation, and one in which an old face appeared at a new orientation.

Observers in the inclusion condition were told to respond ‘old’ to both images of this person, since a view of this person was shown in the practice study session. Observers in the exclusion condition were told to respond ‘old’ only to the face at the identical orientation and the practice test session was given at the end of the study session. Feedback was given during the practice test session to ensure that observers understood that they should respond ‘old’ to a studied face only to orientations that conform to their instructions.

Results and Discussion

We discuss the data from the Inclusion and Exclusion instruction observers separately.

Inclusion Instructions

Data from the Inclusion instructions portion of Experiment 4 are shown in Figure 6. There were only slight differences between the false alarm rates for the 5 test orientations, which were 0.41 (0.011), 0.45 (0.011), 0.45 (0.011), 0.42 (0.011) and 0.45 (0.011) respectively. Correcting the hit rates for the false alarm rates by computing d’ or subtracting the false alarm rates produces only very small changes in the performance values and no differences in the conclusions described below. As a result, we consider hit rates for the 5 study conditions rather than computing d’ values. The curve parameters in Figure 6 are the 5 study orientations, while the abscissa shows the 5 test orientations. Error bars represent ± 1 SE around the mean hit rate for each condition. Circled points correspond to conditions in which the study and test orientations were the same. Recognition should be best in these conditions, and it is. The Figure 6 data show the Inclusion data from Experiment 3 collapsed across all 5 times a particular view was shown; because we study a face only once and then test all 5 orientations, each face is seen 5 times at test. It is important to verify that this design does not affect our results, and two check this we analyzed our data by looking at only the first time a face was tested. These results are somewhat noisy, but are quite similar to the Figure 6 data, demonstrating that showing all 5 views of a face does not artificially produce our results.

We have three targeted comparisons that will address whether symmetric orientation ef-
Effects are evident in recognition memory. First, for items studied at 70°, does recognition performance at -50° exceed that at 10°? Inspection of Figure 7 suggests an improvement near -50°, and this improvement is significant, as demonstrated by a 95% confidence interval on the difference between the two conditions. If the two means are significantly different, the confidence interval on the mean difference will not include zero. The comparison of performance in the -50° and 10° conditions is 0.122 ± .068, which demonstrates that performance in the -50° test view is significantly above performance in the 10° condition.

Our second comparison involves faces studied at -50°. We compare performance at the 10° view with that from the 40° and 70° study views. When combined, these two points are marginally above the 10° performance condition (90% CI: 0.0514 ± 0.0496).

The final comparison involves the 10° study condition. When tested at the -20° view, performance is marginally significantly above the 40° view (90% CI: 0.062±0.055), despite the fact that a) -20° and 40° are both equally distant to 10° in terms of angular difference, and b) -20° is on the other side of the frontal view, which could potentially make it even less similar to 10° than 40° is to 10°.

These three comparisons illustrate that symmetric orientation effects do occur in recognition memory. That two out of the three are only marginally significant should be viewed in the light of the fact that we constructed our design to make it very difficult for symmetric orientation recognition. First, we used unsymmetrized faces with luminance asymmetries. Recall that these same faces showed very poor recognition at the symmetric orientation in Experiment 2. Second, we used test angles that did not correspond to the exact symmetric orientation.

Exclusion Instructions

If observers can accurately distinguish between the original study view and the symmetric orientation view, then we would not expect the symmetric orientation effects described for the Inclusion data above. The hit rate data from the Exclusion instructions are shown in Figure 8. The false alarm rates for the 5 test orientations were 0.24 (0.010), 0.29 (0.011), 0.28 (0.011), 0.28 (0.011) and 0.28 (0.011) respectively, and as with the inclusion data, correcting the hit rates for the false alarm rates by computing d’ or subtracting the false alarm rates from the hit rates produces only very small changes in the performance values and no differences in the conclusions described below. As a result, we again report only hit rates for the 25 experimental conditions.

As with the Inclusion data, observers were most likely to call faces that were studied and tested in the same orientation as 'old'. As study and test orientations began to differ, observers were less likely to say 'old', suggesting that they could discriminate between studied orientations and other orientations. Most importantly, the 70° study condition shows no evidence of an increase in the rate of responding 'old' at the -50° test view, which is a qualitative change from the Inclusion instructions. Data from the -50° study orientation also do not show evidence of an increase in recognition performance at the 40° or 70° test views. Thus it appears from these comparisons that observers can discriminate between the studied view and the symmetric orientation view when the study angles are not close to the frontal view.

However, the ability to distinguish between the study orientation and the symmetric orientation may not be under complete control of the observer. Consider the data from the 10° study condition. When tested at -20° (near the symmetric orientation of -10°) performance is higher than the 40° condition (95% CI: 0.077±0.072). This relation held true in the Inclusion instructions as well (although was only marginally significant), and suggests that observers continue, to some degree, to confuse the symmetric orientation views with the studied views.

In summary, we find evidence for symmetric orientation effects in recognition memory. That we find such effects even when using unsymmetrized faces and test angles that are 10-20° away from the symmetric study angle with unsymmetrized faces suggests that these effects are fairly robust and that observers have abstracted enough information about the faces to overcome differences in luminance asymmetries and orientation changes. This was not the case in Experiment 2, where performance at the (exact) symmetric orientation was below that of the frontal view for unsymmetrized faces.
The data from the exclusion instruction task suggests that observers seem to be able to distinguish between representations that support recognition of the original view and the symmetric orientation view. However, this ability seems to break down for angles near the frontal view.

**Experiment 4**

The results of Experiment 3 suggest that in recognition memory observers rely less on image-based representations that might be disrupted by texture asymmetries. In Experiment 4 we introduced an additional manipulation at study that we hoped would further encourage the use of representations that work in addition to an image-based coding. During the study portion we rotated the heads around the vertical axis $\pm 15^\circ$ away from the study orientation. We anticipated that such a manipulation might provide enough depth-from-motion to allow observers to encode some structural depth information. This abstracted information could then complement an image-based system for the recognition of the symmetric view.

Two lines of evidence suggest that motion can affect the nature of the information stored in memory. McNamara, Diwadkar and Blevins (1998) addressed the viewpoint-dependent nature of scene perception using displays that provided (or inhibited) apparent motion. They showed observers a perspective display of 5 colored dots on a computer monitor. The dots could be rotated to simulate a new viewpoint, and when alternated with the appropriate ISI, strong apparent motion was reported by observers. In a control condition the dots jumped from one side of the screen to the other as well as rotated, which prevents a percept of apparent motion. They then tested the observer's memory for the configuration of dots at novel orientations using an old/new recognition paradigm. Distractor stimuli were composed of the same colored dots in new spatial configurations. They found that recognition for views that fell in between the two views (i.e. the interpolated views) was as good as recognition for the actual study views. These did not hold for the interpolated views in the condition in which apparent motion was prevented. McNamara et al. (1998) concluded that the motion created 'virtual views' in memory in between the endpoint views that facilitated recognition for these interpolated views. Their data suggest that the apparent motion allowed the observers to extract enough structural information about the locations of the dots to infer their relative placement for the interpolated views.

Our face stimuli are considerably more complex than the 5 dots used by McNamara et al. (1998). This rich structure adds additional information that could be used by observers, especially information defined by constraints in which information from one source guides the processing of information from another source. A large literature suggests that depth relations (e.g. Hildreth, Grzywacz, Adelson & Inada, 1990) and possibly the three-dimensional structure of objects can at least partially be recovered from an object by placing it in motion (e.g. Wallach & O'Connell, 1953; Todd & Bressan, 1990). However, the recovery of depth from motion depends in part on constraints provided by the stimulus. One source of information that may provide these constraints is a line of coplanar points. The structure of faces is for the most part bilaterally symmetric, and as a result faces have a series of features run down the center of the forehead and down the nose and chin that make up a particularly salient line of coplanar points. Pizlo and Stevenson (in press) have demonstrated that coplanar lines like the one running down the middle of faces can provide rich structural information when placed into motion. This requires that the observer identify the points as coplanar, which should not be an issue given the fact that humans have vast experience with faces. Pizlo et al (in press) find that shape constancy is best achieved by a stimulus containing planar contours, and that other relations such as symmetry and topological stability also contribute. Human faces contain both bilateral symmetry and a salient line of coplanar points, suggesting that motion may provide strong structural information through the use of these invariants. Thus motion information may provide at least limited structural information about the face that may assist the recognition of faces at symmetric orientations. Note that merely placing an object into motion may not automatically provide additional structural information that would allow recognition of novel viewpoints: Bülthoff & Edelman (1992) compared motion versus static study conditions for wire-frame and amoeba objects, and found no benefit for the motion
conditions. These objects were without constraints such as symmetry and readily-identifiable coplanar points, and as a result the motion information did not prove particularly useful when generalizing to novel viewpoints. This reinforces the conclusion by Pizlo et al (in press) that it is the interaction between regularities in the stimuli and motion that provides structural information.

Although relatively little structure-from-motion work has been done on faces, Hill, Schyns and Akamatsu (1997) used motion sequences with untextured 3D lasercan models of faces, and their results suggest that motion enhances face recognition. They rotated faces from one profile to another and back through a sequence of 5 frames, presenting each frame for 100 ms. In a control condition the ordering of the frames was randomized. Their motion experiment did not allow an investigation of symmetric orientation effects (or performance at any novel orientations), since all 5 test views spanning both sides of the frontal view were shown in the study sequence. The authors report only an overall increase in performance in the motion condition relative to the random motion control, which could imply only that motion stimuli are easier to look at or more informative than random motion displays. This leaves open the question of how motion enhances the recognition of faces: does it provide more overall information by virtue of the smooth nature of the motion, or does motion enable the acquisition of specific types of information (such as limited 3-dimensional structure) that can assist recognition at particular novel viewpoints such as the symmetric orientation? If it does, this would suggest that motion allows observers to extract additional information than that provided by a single image-based representation.

We constructed smooth motion sequences by rotating the face around the vertical axis and compared this condition to two control conditions designed to reduce or eliminate the motion percept. For each of the two study views, five frames were generated for each face, which includes two views that are ± 7.5° from the study view, and two views that were ±15° away from the study view. Rather than use all 5 study views from Experiment 3, we limited our study views to 70° and 35°, and generated frames around these views to create motion sequences. The top images in Figure 8 show the 5 views centered around the 35° study angle, and the bottom row shows the 5 test orientations.

We used three motion sequences. The first provides a smooth motion percept by sequentially showing the 5 frames for 180 ms each for a total of 5760 ms. This provides a rich sensation of the head smoothly rotating back and forth for 4 complete cycles. A random motion control condition was generated by taking the frames from the smooth motion condition and randomizing the sequence such that no two frames repeated. While some accidental sequences will produce a slight perception of motion, overall the sequence shows a face randomly jerking from one view to the next, preventing acquisition of a smooth motion percept. The second control condition reorders the frames so that a slow motion sequence is shown; each view is visible for 720 ms, allowing the face to move through only one complete cycle in 5760 ms. It should be stressed that only the ordering of the frames changed across the motion conditions; the timing and duration parameters were identical, as is the static information available to the observer if the order of the frames is ignored.

We anticipated that the differences between the control and experimental conditions might be somewhat small, and to ensure that we measured any effects of motion on the perception of the symmetric view, we tested the exact symmetric orientation. Thus the five test orientations were 70°, 35°, 0°, -35° and -70°. A face was shown either at 70° or 35° in one of the 3 motion conditions, and tested using static images at all 5 orientations.

Method

Observers

Observers were 149 Indiana University students who received course credit for their participation.

Stimuli

The head models were identical to those used in Experiment 4. Movie sequences were created by rendering 4 views around the 70° and 35° study views that were ±7.5° and ±15° away from the study views. These were presented in full color on the PowerMac 7200, which is able to write the individual images in
less than a screen refresh, making the effective ISI between frames 0 ms. Each frame of the motion sequence was on display for 180 ms, for a total of 5760 ms per sequence.

**Design and Procedure**

Twelve faces were used in the study session, and shown in one of the 6 conditions (2 study orientations x 3 motion conditions) according to a randomized counterbalancing schedule. The instructions were similar to those in Experiment 3, except that the practice study period contained faces that were placed into motion. Observers were told that they would have to recognize the faces at novel orientations, and the practice test session verified that they understood that a previously-seen face at test at a novel orientation was still an old face.

Following the practice study and practice test session, the observers viewed the 12 study faces and then made old/new judgments on all 120 test faces. These faces come from the 12 target faces shown at 5 test orientations (70°, 35°, 0°, -35° and 70°), as well as the 12 distractor faces also shown at the 5 test orientations.

**Results and Discussion**

Observers studied only left-facing faces in Experiment 4, and this may introduce small criterion shifts for right-facing faces. Memory performance is expected to be lower for right-facing test angles, and observers might shift their decision criterion to compensate. As anticipated, there were small but significant differences between the false alarm rates, which were .42, .45, .43, .40 and .39 with a common SEM = 0.010. Correcting for these false alarm rates would allow us to make across-angle comparisons, but we have already established the symmetric orientation effects in Experiment 3. Thus we rely on raw hit-rate data as in Experiments 1-3 and focus on performance differences within a test angle across conditions, as well as the interaction between motion condition and test angle.

The data for Experiment 4 are shown in Figures 9 and 10 for the two study orientations, and show similar effects. The abscissa shows the 5 test orientations, and the three motion conditions produce the three curves. The error bars represent one standard error of the mean.

**Data from the 70° Study View**

Figure 9 shows the data from faces that rotated around the 70° study view. Performance is highest for angles tested at the study view of 70°, and falls for the frontal view, and then shows a recovery for the smooth motion condition. A repeated-measures ANOVA revealed an interaction between motion condition (Smooth, Random or Slow) and test angle (F(8, 1184)=2.27, p<0.05). Inspection of Figure 9 reveals that this interaction derives mainly from differences between the three conditions at the -35 and -70 degree test angle. Restricting the analyses to these test angles reveals a significant difference between the Smooth and Random conditions (F(1, 148)=4.59, p<0.05) and the Smooth and Slow conditions (F(1,148)=7.37, p<0.01). In both cases, performance in the smooth motion condition is greater than either comparison condition, which is consistent with a process that uses aspects of the motion to derive a representation that assists recognition of the symmetric orientation view.

The effects of motion appear to be restricted to angles at and near the symmetric orientation view. There were no differences between the three motion conditions when the analysis was restricted to the 70°, 35° and 0° angles (F(1,148)=3.4, n.s.). In addition, performance was not better overall for the smooth motion condition (F(2, 296)=1.39, n.s.), demonstrating that smooth motion does not provide more information than the other two conditions. The beneficial effects of smooth motion appear to be restricted to angles at or near the symmetric orientation.

**Data from the 35° Study View**

Figure 10 shows the data from the 35° study view, and show effects similar to those from the 70° study view in Figure 9. Performance is highest in all three conditions at the 35° test view, and show evidence of an improvement in performance at the -35 test view for the Smooth motion condition. As with the 70° data, the interaction between motion and test angle is

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2 Note that these changes over test angle and the recovery at the symmetric orientation view are even more apparent when correcting for the false alarm rates via d'. However, it is difficult to compute d' values on individual observers, making statistical analyses problematic. Thus we have restricted our discussion to the hit rates.
significant (F(8, 1184)= 3.00, p<0.01). One contribution to this interaction is that performance at the symmetric orientation view is higher for the smooth motion condition compared against the other two condition (F(1, 148)=4.3, p<0.05). However, performance at the a test view of 35° (corresponding to the study view) does not differ between the smooth motion condition and the other two (F(1,148)<1). As with the 70° data, performance was not better overall for the smooth motion condition (F(2, 296)<1), again demonstrating that smooth motion does not provide more information than the other two motion conditions.

**Motion Assists the Recognition of the Symmetric Orientation View**

The recovery of performance at the symmetric orientation view only for the smooth motion and the interaction between motion and test angle are both consistent with a process that uses motion to derive a representation that assists in the recognition of the symmetric orientation view. How might this be accomplished? We offer a possible mechanism that is based on the recovery of local three-dimensional information in the form of the contour of the face.

**Extraction of Local 3D Structure**

One process that might provide good recognition at the symmetric orientation is the possibility that motion may enhance the perception of lines of coplanar points. Faces are (mostly) bilaterally symmetric, and as a result have a series of features run down the center of the forehead and down the nose and chin that make up a particularly salient line of coplanar points. Pizlo and Stevenson (in press) have demonstrated that coplanar lines like the one running down the middle of faces can provide rich structural information when placed into motion. This requires that the observer identify the points as coplanar, which should not be a issue given the fact that humans have vast experience with faces. Pizlo et al (in press) find that shape constancy is best achieved by a stimulus containing planar contours, and that other relations such as symmetry and topological stability also contribute. Our faces contain both bilateral symmetry and a salient line of coplanar points, suggesting that motion may provide strong structural information through the use of these invariants. Thus motion information may provide at least limited structural information about the face that may assist the recognition of faces at symmetric orientations. Note that merely placing an object into motion may not automatically provide additional structural information that would allow recognition of novel viewpoints: Bültöff & Edelman (1992) compared motion verses static study conditions for wire-frame and amoeba objects, and found no benefit for the motion conditions. These objects were without constraints such as symmetry and readily-identifiable coplanar points, and as a result the motion information did not prove particularly useful when generalizing to novel viewpoints. This reinforces Pizlo et al (in press) conclusion that it is the interaction between regularities in the stimuli and motion that provides structural information.

Our test stimuli were static, thus requiring observers to extract information about the contour of the face from a single image. The frontal view provides essentially no information about the contour of the face, but the symmetric orientation view does allow some contour information to be inferred, thus supporting good recognition at the symmetric orientation view, but only for the smooth motion condition.

**Performance at the study view**

For both the 70° and 35° study views, performance at the study view did not differ for the three motion conditions. Why is there no benefit overall for the smooth motion condition? One explanation is that all three motion conditions provide enough image-based information that allows an image-based representation to recognize the original view. However, this representation does not work well for the symmetric orientation due to texture or structural asymmetries, and thus the observer relies on additional information. The data from Experiment 4 demonstrate that observers rely on information derived from smooth motion to enhance the recognition at the symmetric orientation view, which augments the image-based representation.

**Accounting for Additional Effects**

In addition to the differences between motion conditions described above, Figure 10 shows that performance at the 70° test view for items studied at 35° also shows large differences between the three conditions.
(F(2,296)=6.11, p<0.05). We did not anticipate this result, and we offer only this admittedly post-hoc explanation.

For our stimuli, information in the 70° view about the ridge line of the eyes or the protrusion of the mouth (as estimated by the corner of the mouth) suggest more depth in the face than is actually present. If observers try to obtain contour information from the static 70° view they will not match the contour provided by smooth motion rotations around 35°. That is, the smooth motion condition places a representation into memory that includes shape information that is difficult to match to the static 70° test angle, and this produces decrements in performance at the 70° test angles for the smooth motion condition.

Although it may be difficult to go from a 35° study stimulus to a 70° test stimulus, the reverse may be possible. The rotating 70° study stimulus may provide enough contour information to enable good recognition at the -35° test stimulus, which would account for the slightly better recognition performance at -35° than -70° in Figure 9.

**Summary of Experiment 4**

The results of Experiment 4 are consistent across the two study orientations: the motion conditions show an interaction across test angles, which results from the fact that performance at and near the symmetric orientation is facilitated by smooth motion. Note, however, that this improvement is limited to angles at or near the symmetric orientation; at other test views performance in the smooth motion conditions was equivalent to or worse than the other two conditions. Thus the information contained in the smooth motion display does not provide a representation that is viewpoint invariant; instead, the information provided by the motion provides a limited benefit at the symmetric orientation. One possible explanation is that performance at the symmetric orientation is assisted by the encoding of shape information about the contour of the face. This allows some recognition of the angles near the symmetric orientation because enough shape information is available from the static test view to recover the contour of the face and therefore match the memory representation. Recognition at the 0° view is no better for the smooth motion condition, because it is difficult to extract contour information from a frontal view, and thus local depth information obtained from 35° or 70° is of no use.

In summary, the results of Experiment 4 demonstrate the need for an explanation of symmetric orientation effects that goes beyond a static, image-based comparison, and does so using only fully-upright faces. The representation appears to include information derived from smooth motion, which may include local depth information obtained from a sequential analysis of coplanar points. This depth information is specific to the symmetric orientation view, which due to its static nature at test is the only view at which depth relations similar to the study orientation view might be recovered.

**General Discussion**

The results of these four experiments paint a somewhat different picture of the mechanisms that subserve the recognition of faces at symmetric views of the study orientation than that proposed in the literature. Previous research suggests that the symmetric view effects resulted from fairly low-level visual mechanisms working on relatively raw images. As Vetter et al. (1994) point out, bilaterally symmetric objects such as faces do not require knowledge of three-dimensional structure in order to generate the symmetric orientation view. The symmetric orientation can be recognized by reflecting the major landmark points of the studied view across the vertical axis. The results of the present experiments suggest that observers use more information than that provided by an image-based transformation such as landmark reflection. Instead, inverted faces seem to rely less on a flipped image-based template and more on individual features regardless of their exact configuration. In Experiment 2, tilting a face allows observers to overcome texture asymmetries and in some cases improve performance over upright faces. Again, it seems likely that observers are using a representation that does not treat the face as a single image, but instead are using a different set of primitive features and their categorical relations. In Experiment 4, smooth motion enhanced recognition of the symmetric orientation view, perhaps by allowing observers to abstract information about the structure of the faces that provides limited generalization to those test views in which contour information can be extracted from static test views. Whatever the nature of the representations, the proc-
esses that enable recognition of the symmetric orientation are for the most part under cognitive control, since observers can and do differentiate between real and symmetric orientations if necessary, as in Experiment 3.

The Nature of the Symmetry Mechanisms

Our data allow some conclusions about the nature of the symmetry mechanisms that support the recognition of the symmetric orientation of a study view for our bilaterally-symmetric faces. It appears that an image-based representation is well suited for the recognition of symmetrized faces at the symmetric orientation, but that it breaks down in the presence of asymmetries in the face (such as texture or structure) or external asymmetries brought on by tilting the face. Inversion of the face also appears to prevent an easy image-based comparison. Under some circumstances, observers bring additional representations to bear that actually prove superior to the image-based representation.

Observers by and large can discriminate between a studied view and the symmetric view, since virtually no symmetric view effects were observed in the Exclusion condition of Experiment 3. The exception appears to be faces that were studied at 10° and show significantly higher error rates in the -20° condition than the 40° condition in the Exclusion condition of Experiment 3.

The results of our motion conditions of Experiment 4 suggest that part of the processes that enable symmetric view recognition relate to an encoding of the structural information in faces through the analysis of coplanar points. Given that in naturalistic settings faces are almost always moving, the current literature may underestimate the role that these coplanar points play in the recognition of faces.

An open question is how recognition of the symmetric orientation view maps on to related fields such as the identification of symmetry within an object (such as a face seen in a frontal view). Despite a fairly well-developed field (See Tyler, 1994, 1995 for reviews), no consensus has been reached about the underlying neuro-physiological underpinnings of symmetry detection. However, such a model, when found, may also be able to account for the image-based representation proposed by Troje & Bülthoff (1998). Whether it can then be extended to include elements of motion and categorical relations between individual features, or whether an additional representation is required, must then be addressed.

Author Notes

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Figure 1. Example stimuli from Experiment 1 for the condition in which a symmetric orientation view is tested. Other conditions tested the same three eye-raised stimuli at either the original orientation or the frontal view.
Figure 2. Hit Rates from upright faces from Experiment 1.
Figure 3. Hit Rates for inverted faces from Experiment 1.
Figure 4. Explanation of predicted interaction in Experiment 2 between Test Angle and Tilt for Unsymmetrized Faces.
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<td><img src="image6" alt="Symmetric Angle" /></td>
<td><img src="image7" alt="Original Angle, Tilted" /></td>
<td><img src="image8" alt="Symmetric Angle, Tilted" /></td>
</tr>
<tr>
<td>Smaller Difference</td>
<td><img src="image9" alt="Original Angle" /></td>
<td><img src="image10" alt="Symmetric Angle" /></td>
<td><img src="image11" alt="Original Angle, Tilted" /></td>
<td><img src="image12" alt="Symmetric Angle, Tilted" /></td>
</tr>
<tr>
<td>Proportion Correct</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Figure 5. Results from Experiment 2.
Figure 6. Data from Experiment 3 for Inclusion instructions. Circled points represent conditions in which study and test views were identical. Error bars represent ± 1 SEM.
Figure 7. Data from Experiment 3 for Exclusion instructions. Circled points represent conditions in which study and test views were identical. Error bars represent ± 1 SEM.
Figure 8. Experiment 3 stimuli. Top row: 5 frames of a motion sequence centered around the 35° viewpoint. These were shown for 5 complete cycles at study. Bottom row: Five test viewpoints used in Experiment 3, which were static.
Figure 9. Data from Experiment 3 for the 70° study view conditions. The points have been slightly offset horizontally for clarity. Error bars represent ± 1 SEM.
Figure 10. Data from Experiment 3 for the 35° study view conditions. The points have been slightly offset horizontally for clarity. Error bars represent ± 1 SEM.