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A Methodology for Predicting User Curvature Perception of 3D Objects

Nayan Chawla* University of Central Florida
Joseph J. LaViola Jr.† University of Central Florida
Ryan P. McMahan‡ University of Central Florida

Abstract

One's perception of an object's curvature affects its perceived appeal, realism, and even distance. However, studies indicate curvature perception often differs from the object's mathematically defined curvature, and no alternative for predicting curvature perception exists. We present two pairwise-comparison studies where participants selected objects perceived to have more curvature. The results indicate some objects are perceived to have significantly more curvature than others, yielding distinct perceptual clusters. We then demonstrate that traditional curvature measures poorly predict curvature perception, and present a novel methodology with results proving it a capable indicator of how a 3D object's curvature will be perceived.

Index Terms: Computing methodologies—Computer graphics—Perception

1 Introduction

The perception of a 3D object's curvature has been shown to heavily impact other facets of its visual perception and user experience, such as luminance [7] and depth [1]. For instance, there is recent evidence that color significantly affects perceived depth of objects with curved surfaces but not objects with flat surfaces [2]. This is important to virtual reality (VR) and augmented reality (VR) applications, where the depths of objects are often misjudged [6].

However, studies on the effects of curvature perception often employ classical measures such as Gaussian or mean curvature, which are not representative of the extrinsic shape of a surface [8]. Thus, they fail to yield accurate predictions of either local or global curvature perception [10], where local refers to a patch of a surface and global refers to the whole. The shape index and curvedness measures [8] are two popular alternatives, but these measures have been shown to underestimate local curvature perception and depth [11]. Additionally, these alternative measures are not equipped to predict global curvature perception, as they vary widely across a surface's local features [5]. The inability to estimate global perception of curvature, along with the myriad of issues with the classical measures, indicates a clear need for a better approach to predicting user curvature perception.

We present several contributions towards improving understanding of perception of curvature. First, we present two studies that employed paired comparisons of 3D meshes to investigate how users perceived both local and global curvature. To evaluate traditional curvature metrics for estimating both local and global curvature perception, we computed measures of central tendency on their results across all vertices for each 3D mesh. Our results indicate that the traditional curvature metrics are generally poor predictors of curvature perception. In response to these results, we propose a new methodology for measuring user curvature perception. Using the same analysis, our results indicate this methodology is a much better predictor of perceived curvature.

*e-mail: nayan.chawla@ucf.edu
†e-mail: jjl@cs.ucf.edu
‡e-mail: rpm@ucf.edu

2 Perceptual Studies

Each study consisted of one online Qualtrics survey that lasted approximately 5 minutes. Each participant completed a background survey that captured their demographics, education, and technology experience. Afterwards, the participant completed the paired comparisons. We adapted the procedure of Dunn-Rankin et al. [3]. Participants were presented with pairs of objects in randomized order, with only one pair presented on the page at a time. The order of the objects within the pair was also randomized (i.e., which object appeared on the left was randomized). The participant was instructed to "Select the object from the pair that you think has the most curvature as quickly as possible". Fig. 1 shows a screenshot of a pair of objects presented in the global curvature study.

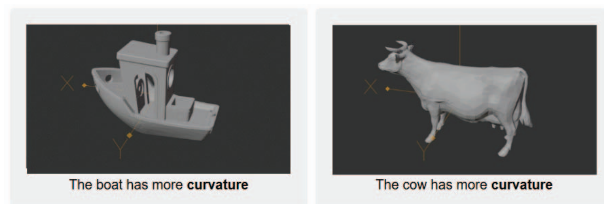

Figure 1: Example paired comparison from global curvature study.

We followed the methodology and analysis presented by Ledda et al. [9] for paired-comparison experiments. Figures 2 and 3 show our perceptually distinct groups from lowest to highest score, where objects in different groups are perceptually distinct in terms of curvature, and indicated by lines.

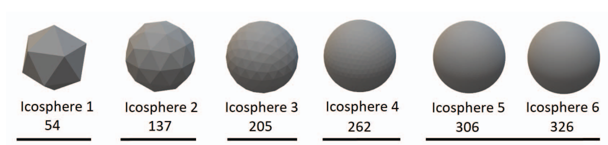

Figure 2: The continuum of icospheres by increasing perceived curvature based on aggregated preference scores.

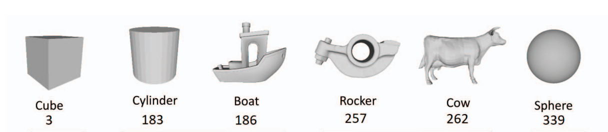

Figure 3: The continuum of common 3D test meshes by increasing perceived curvature based on aggregated preference scores.

3 Perceptual Accuracy of Traditional Measures

We investigated how accurately traditional curvature measures could estimate human curvature perception. Because these traditional measures estimate local curvature for each individual vertex, we

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used a method for reducing all of the local curvatures of a mesh's vertices down to a single feature, for extracting rankings of the meshes similar to the results of our studies. We used the methodology presented by Durduran [4], who employed k-means clustering on central tendency measures to investigate the feasibility of automatically classifying urban land cover data.

With the exception of curvedness, the traditional measures failed to yield the same clusters as our local or global curvature perception studies. More importantly, these measures failed to indicate that the cube had the least curvature and the sphere had the most, among the six 3D test models. These results reinforce the observation by Koenderink and van Door [8] that Gaussian and mean curvature are not very indicative of local shape, let alone global shape.

On the other hand, all four of the central tendency measures of curvedness aligned with the results of our local curvature perception study. This reinforces the work by Koenderink and van Door [8], in which they propose curvedness as a better measure of the intensity of a surface curvature. However, the curvedness measure failed to yield any clusters that matched the perceptual groupings found in our global curvature perception study. This indicates that while curvedness is useful for predicting perception of local curvature, it is a poor predictor of global curvature perception.

4 Our Proposed Methodology

We now present our novel methodology, which uses the averaged and thresholded angles between face normals to accurately estimate curvature perception. Our methodology yields a positive number that inversely correlates with human curvature perception, where a number closer to zero indicates that a local face has greater perceived curvature than faces with higher values. This value is based on calculating the dihedral angle, δ, which is the smallest angle (in degrees) between the normal vectors of two adjacent faces. We use the average δ between a given face and the set of faces adjacent to it, to calculate the amount of inverse curvature that the face has. For example, the faces that are adjacent to an edge of a cube will have a higher inverse curvature than adjacent faces on a sphere because of the sharper angle at the cube's edge. We refer to the average of the dihedral angles between a face and its adjacent neighbors as ρ_κ.

In addition to being scale invariant, unlike the traditional curvature measures (except shape index), the results of our methodology are also invariant to dense meshes that contain numerous adjacent faces with the same face normal. For example, a 12-faced cube will yield the same result as a 48-faced cube. To accomplish this, we only account for adjacent faces with face normals above a set threshold (i.e. $\delta > 1x10^{-5}$). This threshold was selected based on errors detected in our original cube mesh.

Calculating ρ_κ provides a value negatively correlated with the overall curvature about the face f_i. For example, refer to Table 2. The faces of a conventional 12-faced cube (with 2 faces per side) each have a ρ_κ of 90.0 due to having two 90° adjacent faces. Note, each face also has one 0° adjacent face, but this face is ignored due to the δ threshold requirement of our methodology. On the other hand, the faces of a 32,040-faced sphere have an average ρ_κ of 1.222 due to having adjacent faces with similar small angles. Since the average ρ_κ for the sphere's faces is much smaller than for the cube's faces, this clearly indicates that the sphere has much more curvature than the cube, due to the inverse correlation of our results and human curvature perception.

5 Results

Table 1 shows the results of the central tendency measures and k-means clustering when applied to the results of our methodology (ρ_κ) for each icosphere in our local curvature perception study. The results show that our methodology yields the same clusters of icospheres as our local curvature perception study for all of the central tendency measures. Table 2 shows the results of the central tendency measures and k-means clustering for our methodology for each common 3D model in our global curvature perception study. Unlike the results of the traditional curvature measures, these results indicate that our methodology is a good indicator of global curvature perception. Furthermore, it is important to note that the median measure yielded the exact same clusters as our global perceptual groupings, which indicates that it is better at estimating perceived curvature than the other central tendency measures.

Table 1: The results of our novel methodology on the icospheres.

Perceptual Scores and Clusters		Curvature Perception ($\rho\kappa$) *A*	*H*	*Md*	*Mo*
Icosphere 1	54	41.810	41.810	41.810	41.810
Icosphere 2	137	20.244	20.157	20.982	20.982
Icosphere 3	205	9.996	9.984	10.131	10.298
Icosphere 4	262	4.981	4.965	5.010	4.648
Icosphere 5	306	2.488	2.478	2.521	2.560
Icosphere 6	326	1.244	1.238	1.253	1.287

Table 2: The results of our novel methodology for the test meshes.

Perceptual Scores and Clusters		Curvature Perception ($\rho\kappa$) *A*	*H*	*Md*	*Mo*
Cube	3	90.000	90.000	90.000	90.000
Cylinder	183	33.391	31.969	33.747	30.000
Boat	186	31.026	0.027	24.522	4.605
Rocker	257	9.460	5.347	8.356	2.740
Cow	262	17.801	11.290	15.108	11.303
Sphere	339	1.222	1.124	1.190	1.327

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