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# Effects of surface reflectance on local second order shape estimation in dynamic scenes

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ABSTRACT

In dynamic scenes, relative motion between the object, the observer, and/or the environment projects as dynamic visual information onto the retina (optic flow) that facilitates 3D shape perception. When the object is diffusely reflective, e.g. a matte painted surface, this optic flow is directly linked to object shape, a property found at the foundations of most traditional shape-from-motion (SfM) schemes. When the object is specular, the corresponding *specular flow* is related to shape *curvature*, a regime change that challenges the visual system to determine concurrently both the shape and the distortions of the (sometimes unknown) environment reflected from its surface. While human observers are able to judge the global 3D shape of most specular objects, shape-from-specular-flow (SFSF) is not veridical. In fact, recent studies have also shown systematic biases in the perceived motion of such objects. Here we focus on the perception of *local shape from specular flow* and compare it to that of matte-textured rotating objects. Observers judged local surface shape by adjusting *a rotation and scale invariant shape index probe*. Compared to shape judgments of static objects we find that object motion decreases intra-observer variability in local shape estimation. Moreover, object motion introduces systematic changes in perceived shape between matte-textured and specular conditions. Taken together, this study provides a new insight toward the contribution of motion and surface material to local shape perception.



## 1. Introduction

The internal representation of the 3D geometry of physical objects is vital for allowing humans to interact with the physical world. From threading a needle, grasping a coffee cup, or carefully stepping along a staircase, the estimation of 3D shape from visual cues covers much of our daily activities. Since the image reflected off an object depends critically on its surface properties, our visual system is faced with a material-shape ambiguity that in practice requires the estimation of both. This ambiguity is particularly severe for specular objects and unknown illumination environments since it is straight forward to manipulate both the shape and the environment to generate any given image (e.g., Fleming, Drorr, & Adelson, 2003). One strategy employed by humans for better observing and reconstructing the 3D shape of objects includes the incorporation of relative motion between the object, the environment, and the observer (e.g., by moving the object or the observer's head or body). Such motion projects as dynamic visual information onto the retina (optic flow) and has been shown to improve or facilitate 3D shape perception (Wallach & O'connell, 1953; Landy et al., 1991; Bradley, Chang, & Andersen, 1998). These studies most often assume that the surface of the object is matte (i.e., diffusely reflecting), a condition that links the optic flow directly to first order shape properties. When the object is specular, however, the corresponding *specular flow* is tightly related to object *curvature* (Koenderink & Van Doorn, 1980; Adato et al., 2010), a property that manifests itself even in partially specular objects (e.g., sweet peppers or other types of fruits). This regime change is further complicated by dependency on the nature of motion, an effect that was analyzed computationally (Adato et al., 2010) and observed perceptually (Hartung & Kersten, 2002; Sakano & Ando, 2008; Doerschner et al., 2011). It is now clear that specular flow behaves very differently from other types of optical flow (e.g. Adato, Zickler, & Ben-Shahar, 2011; Adato & Ben-Shahar, 2011), leaving even its robust estimation an open question.

Previous work by our group has shown that shape-associated estimates for *moving* specular objects are qualitatively different

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than those for matte-textured ones. For example, specular flow may bias the perceived object rotation axis (Doerschner et al., 2013) or may produce illusory non-rigid percepts (Doerschner & Kersten, 2007; Doerschner, Kersten, & Schrater, 2011). The perception of local shape from *static* specular reflections has also been studied but are currently inconclusive (e.g., compare the different conclusions in Fleming, Torralba, and Adelson (2004), Savarese, Fei-Fei, and Perona (2004)). In contrast, no systematic exploration of local shape estimation has been done for *moving* specular objects. This paper describes the first step in this direction.

The study of local shape perception of moving objects presents a challenge: Most related studies have used the attitude probe (Koenderink, Van Doorn, & Kappers, 1992), which is often referred to as 'gauge figure probe'. This method is relatively easy to implement in static image stimuli (Wijntjes, 2012), but for rotating objects it becomes problematic. When the stimulus is rotating, the attitude probe has to rotate along, giving away potentially valuable information to the observer. This problem arises because the attitude probe assesses the first order local shape which is not rotation invariant. Therefore, one needs a rotationally invariant shape probe to measure the 3D perception of a rotating stimulus. To meet this challenge we employ a novel, second order shape probe based on the shape index described by Koenderink and van Doorn (1992), Koenderink, van Doorn, and Wagemans (2014).

Using this probe, we address two main questions– can observers estimate the local shape of moving objects and are there any differences in perceived local shape between moving matte-textured and specularly-reflecting objects. The two experiments that follow answer both questions in the affirmative. Taken together, our study provides new insights into the role of motion and surface material in local second order shape perception.

## 2. Methods

### 2.1. Overview

We conducted two behavioral experiments to investigate the effect of surface reflectance on perceived local surface shape in dynamic scenes. Object reflectance properties (matte-textured vs. specular) and their motion (rotating vs. static) was varied within and across experimental sessions, respectively. Observers used a rotation invariant shape index probe to make categorical shape judgments of local surface patches marked on the object. We hypothesized that surface reflectance may modulate perceived local shape in dynamic scenes. In the analysis we correlated observers' shape estimates with theoretical surface curvature values and computed several metrics that capture variation in shape estimation. Static conditions served as baseline measures and we expected to find no systematic differences in shape estimation across surface materials for those trials.

In *Experiment 1* we studied local shape perception of simple objects, where the border – as for any smooth and compact shape – serves as boundary condition for local shape inference. At the boundary, the shape is either convex or saddle-shaped, depending on the curvature of the occluding boundary, and this (categorically) unambiguous information may help observers to integrate shape information from outside to inside. However, when the shape is complex and its variations more numerous, this integration process becomes more difficult and prone to errors. Thus, to diminish the potential influence of the occluding boundary on local shape perception, we conducted a second experiment similar to the first but with a more complex object. In general, we expected observers' shape estimates to deviate more from theoretical curvature values towards the interior of such a complex shape – while not necessarily being less consistent in their shape estimates across conditions – compared to judgments made for simple objects. We also expected to find changes in perceived local shape across material conditions. Details of stimuli, experimental setup, procedure and analysis are described next.

### 2.2. Stimuli

*Shape.* In *Experiment 1* we used two parametric shapes ('furrow' and 'dimple' as defined in Koenderink and Van Doorn (1980)[1], and used in Nefs, Koenderink, and Kappers (2006)), that were shown to observers from both generic and more accidental viewpoints (Fig. 1A and B). We varied viewpoint in order to obtain shape judgments from different parts of the object and to investigate whether shape estimates for a given location change under different viewing conditions (dots 1 and 3 in Fig. 1A and B, respectively). Simple objects subtended approximately 11 degrees visual angle. To generate the novel complex object in *Experiment 2* (Fig. 1C) we applied randomly determined sinusoidal perturbations to a sphere using 3DS MAX ©Autodesk. This object subtended approximately 9.5 degrees visual angle and, unlike the parametric shapes, it was not symmetric.

*Motion.* Dynamic trials presented objects rotating back and forth 10 degrees at a rate of 0.2 degrees/frame and 60 frames per second (12 degrees/s) around the vertical axis (Movies can be found at katja.bilkent.edu.tr/localshape).

*Reflectance.* The 3D shapes were rendered using *environment mapping* (Debevec, 2002). In this technique, the light arriving from all directions at a point in 3D space is captured and stored in a *light probe*, a high dynamic-range spherical image. This image can subsequently be used as an extended light source infinitely far away from the to-be-rendered object. As with any 2D image, the spatial structure of these light probes can be manipulated, though care must be practiced to properly define the desired operations on a sphere. The focus of our study was reflectance-specific motion and not the color or spatial content of the reflected light probe. We therefore desaturated and phase-scrambled (using spherical harmonics) Debevec's *Grace* probe (Debevec, 2002) before using it to render our stimuli.

When objects were *static*, their rendered image was consistent with that of a specularly-reflecting object, e.g., with characteristic compressions at high curvature points. However, the specific manipulations we applied on the light probes resulted in static objects that did not 'look' specular but rather matte and textured. (See Supplementary Fig. 1).

In order to create a *matte-textured* appearance of objects in *dynamic* trials, the specularly-reflected light probe image was "stuck on" to the object (Doerschner et al., 2011), creating a structure from motion consistent with a diffusely- reflecting, textured object. Dynamic *specular* objects elicited characteristic specular flow motion patterns, making them appear shiny when moving (Doerschner et al., 2011).

*Shape probe and sampling.* We used a novel shape probe to assess local shape perception (Fig. 1D), introduced recently by Koenderink, van Doorn, and Wagemans (2014). The probe consisted of five categorical shape indices corresponding to generic surface patches: 'cap', 'ridge', 'saddle', 'rut', 'cup'. This probe has the advantage over the commonly used gauge figure (Koenderink & van Doorn, 1992) in that it measures local shape (as opposed to surface attitude), it is invariant under rotations and scale (just as the local shape itself), and it corresponds to the three prototypical surface shapes – elliptic (concave and convex), parabolic (concave and convex), and hyperbolic (Do Carmo, 1976).

[1] Note that while we used qualitatively similar shapes, the geometry of our 'furrow' deviates from the one defined by Koenderink and Van Doorn (1980).