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Implicit encoding of extrinsic object properties in stored representations mediating recognition: Evidence from shadow-specific repetition priming

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ABSTRACT

This study investigated whether, and under what conditions, stored shape representations mediating recognition encode extrinsic object properties that vary according to viewing conditions. This was examined in relation to cast shadow. Observers ($N = 90$) first memorised a subset of 3D multi-part novel objects from a limited range of viewpoints rendered with either no shadow, object internal shadow, or both object internal and external (ground) plane shadow. During a subsequent test phase previously memorised targets were discriminated from visually similar distractors across learned and novel views following brief presentation of a same-shape masked prime. The primes contained either matching or mismatching shadow rendering from the training condition. The results showed a recognition advantage for objects memorised with object internal shadow. In addition, objects encoded with internal shadow were primed more strongly by matching internal shadow primes, than by same shape primes with either no shadow or both object internal and external (ground) shadow. This pattern of priming effects generalises to previously unseen views of targets rendered with object internal shadow. The results suggest that the object recognition system contains a level of stored representation at which shape and the extrinsic object property of cast shadow are bound. We propose that this occurs when cast shadow cannot be discounted during perception on the basis of external cues to the scene lighting model.

One of the most remarkable aspects of human vision is our ability to recognize three-dimensional objects across variations in sensory input (e.g., Harris et al., 2008; Hummel, 2013; Leek & Johnston, 2006; Tarr & Bülthoff, 1995). Object recognition is generally presumed to require the computation of a perceptual description of object shape and the subsequent matching (or indexing) of this description to a stored shape representation held in long-term memory (e.g., Biederman, 1987; Davitt et al., 2014; Hummel, 2013; Leek et al., 2009, 2012; Marr & Nishihara, 1978). A fundamental issue concerns the structure and content of these stored representations. In ontological terms (e.g., Lewis, 1983) some properties of objects may be regarded as *intrinsically* associated with object identity such as three-dimensional (3D) shape, texture and scale. Such properties (for the most part) may be assumed to be defining characteristics that are stored as part of object knowledge. In contrast, other properties are only *extrinsically* associated with object identity such as cast shadow, shading and brightness. These properties are variable and highly dependent on viewing conditions (e.g., scene structure, luminance direction and intensity). A fundamental question for theories of object recognition is whether, and under what conditions, extrinsic object properties are also encoded in stored object representations.

Central to this issue is that current theories of recognition make different claims about the abstractness of stored object representations (Hummel, 2013). Some models allow for the binding of shape and extrinsic features in image-based templates (Riesenhuber & Poggio, 1999; Serre, Oliva, & Poggio, 2007; Tarr & Bülthoff, 1995). These can be contrasted with structural description models in which extrinsic object properties must be discounted during perceptual processing, and thus not encoded in stored representations (e.g., Biederman, 1987; Hummel & Biederman, 1992; Leek et al., 2009; Leek, Reppa, & Arguin, 2005; Marr & Nishihara, 1978). In this study we examine this issue in relation to the encoding of extrinsic information about shape that is related to cast shadow - which we use as a case in point.[1]

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[1] Cast shadow can also be formally distinguished from attached shadow and shading (see Casati, 2004; Elder et al., 2004; Mamassian, Knill, & Kersten, 1998). However, all can be regarded as extrinsic object properties for the purposes of the present study. Here we restricted our investigation to cast shadow.

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Cast shadow is an ubiquitous property of natural scenes, and arises from the occlusion of light by one surface or object upon another, which can be cast onto another surface of the occluding object, the surface of a different object or the ground (e.g., Casati, 2004; Dee & Santos, 2011; Elder et al., 2004; Knill, Mamassian, & Kersten, 1997; Mamassian, Knill, & Kersten, 1998). Here we distinguish between cast shadow that is attached to the surfaces of an object (which we refer to as '*object internal shadow*'), and shadow that is cast across a ground plane on which the object rests (which we refer to as '*object external shadow*') - (see Fig. 1). Cast shadow can create spurious edge boundaries, and is dependent on surface reflectance properties, ambient lighting and source direction (i.e., the lighting model) as well as scene content, organisation and structure. Even so, there is evidence that, when combined with other assumptions about the scene lighting model (e.g., the 'light from above' prior), shadow can provide valuable information that facilitates the perceptual interpretation of 3D shape and scene structure (e.g., Aubin & Arguin, 2014; Casati, 2004; Castiello, 2001; Cavanagh & Leclerc, 1989; Dee & Santos, 2011; Enns & Rensink, 1990; Kleffner & Ramachandran, 1992; Knill, Mamassian, & Kersten, 1997; Madison, Thompson, & Kersten, 2001; Mamassian, Knill, & Kersten, 1998; Ramachandran, 1988). At the same time, there is empirical evidence supporting the existence of a shadow discounting mechanism in perception (Rensink & Cavanagh, 2004). From a computational perspective this makes sense as one might suppose that shadow (like other extrinsic object properties) is ultimately discounted to facilitate indexing a stored (shadow-invariant) shape representation.

Previous studies do not provide clear evidence on this issue. Tarr, Kersten, and Bulthoff (1998) presented a series of studies in which observers matched the shape of sequentially presented, masked, 3D surface-rendered novel objects under the same or different lighting conditions. The results showed that perceptual matching was less efficient for same shape stimulus pairs when the lighting/shadow was different compared to when it was identical - consistent with the hypothesis that shadow can assist the perceptual recovery of object shape. In another experiment the status of cast shadow in stored object representations was examined. Observers first memorised a sub-set of novel objects rendered with object internal shadow, and they were then asked to identify the same objects from learned and novel viewpoints with either the same or a different shadow rendering. The results were equivocal. Whilst there was some evidence that performance was better for recognition of targets rendered with the same shadow shown in the training phase, this was only found in two out of five analyses. Furthermore, more recent evidence reported by Braje, Legge, and Kersten (2000) based on the naming of common objects failed to find evidence for shadow-specific encoding in a task in which observers named blurred or un-blurred photographic images of fruits and vegetables with or without cast shadow. Thus, current evidence about whether stored representations encode extrinsic object properties like shadow remains inconclusive.

While shadow can (at least under some conditions) facilitate the perceptual interpretation of 3D object structure (e.g., Cavanagh & Leclerc, 1989; Kleffner & Ramachandran, 1992; Knill, Mamassian, & Kersten, 1997; Ramachandran, 1988), we might hypothesise that the likelihood of object internal shadow being bound within a stored shape representation depends on the extent to which it can be distinguished from shape during perceptual processing. One potentially important cue that facilitates the segmentation of shape from object internal shadow is knowledge about the scene lighting model. This can be inferred from sensory cues (such as the position and direction of the light source, shading gradients and the dispersion of shadow on the ground plane), and constrained by a priori assumptions such as the 'lighting from above' prior (e.g., Casati, 2004; Enns & Rensink, 1990; Kleffner & Ramachandran, 1992). Thus, the availability of cues to the scene lighting model may play a key role in determining whether or not shape and object internal shadow are bound in stored shape representations.

The current study was designed to examine these issues in order to elucidate the conditions under which stored shape representations mediating recognition encode extrinsic object properties. Unlike previous studies, we used a repetition priming paradigm (e.g., Arguin & Leek, 2003) to assess the implicit processing of object shadow during a recognition memory task. To do this we created a set of surface rendered novel 3D objects in order to precisely control observer familiarity (with both object shape and viewpoint). Different groups of observers were trained to identify a sub-set of these objects at three viewpoints under three different lighting conditions: no shadow, object internal shadow only, and both object internal and external shadow. During a subsequent test phase targets were shown at previously trained and novel viewpoints and discriminated from visually similar distractors. On some trials targets were preceded by a brief masked same-shape prime containing either matching or mismatching shadow rendering from the learning condition. There were two predictions: First, if object internal shadow is encoded in the stored representations mediating recognition the magnitude of priming for same-shape prime-target pairs should be sensitive to repetition of object internal shadow. Second, if the binding of shape and object internal shadow depends on the availability of cues to facilitate shape-shadow

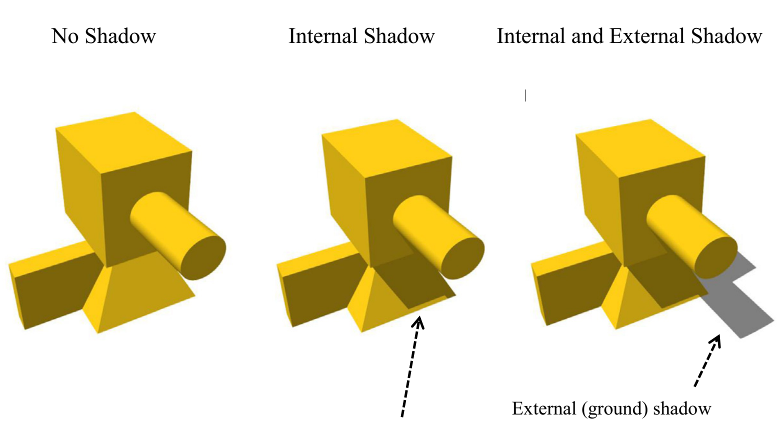

Fig. 1. Illustration of the contrast between object rendering with no shadow, object internal shadow only, and both object internal and external shadow.