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Visual perception of complex shape-transforming processes

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ABSTRACT

Morphogenesis—or the origin of complex natural form—has long fascinated researchers from practically every branch of science. However, we know practically nothing about how we perceive and understand such processes. Here, we measured how observers visually infer shape-transforming processes. Participants viewed pairs of objects ('before' and 'after' a transformation) and identified points that corresponded across the transformation. This allowed us to map out in spatial detail how perceived shape and space were affected by the transformations. Participants' responses were strikingly accurate and mutually consistent for a wide range of non-rigid transformations including complex growth-like processes. A zero-free-parameter model based on matching and interpolating/extrapolating the positions of high-salience contour features predicts the data surprisingly well, suggesting observers infer spatial correspondences relative to key landmarks. Together, our findings reveal the operation of specific perceptual organization processes that make us remarkably adept at identifying correspondences across complex shape-transforming processes by using salient object features. We suggest that these abilities, which allow us to parse and interpret the causally significant features of shapes, are invaluable for many tasks that involve 'making sense' of shape.

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1. Introduction

Every object in our environment—whether a shoe, a starfish or a dollop of cream—has a specific shape, which we readily perceive and can use for recognition and categorization. But where do those shapes come from in the first place? All physical objects and materials end up with particular shapes due to some kind of *generative process*, such as manufacture, biological growth, or self-organization. These shape-forming, morphogenic processes have long fascinated and beguiled researchers from practically every branch of science. However, despite dramatic advances in our understanding of how physical (Chen, Wen, Janmey, Crocker, & Yodh, 2010; Ferziger & Peric, 2012), chemical (Fahlman, 2011; Inostroza-Brito et al., 2015) and biological (Boettiger, Ermentrout, & Oster, 2009; Carlson, 2013; Paluch & Heisenberg, 2009) processes generate complex shapes, we still know surprisingly little about how we perceive and understand such processes (Atit, Shipley, & Tikoff, 2013; Bedford & Mansson, 2010; Chen & Scholl, 2015; Cutting, 1982; Dubinskiy & Zhu, 2003; Feldman, 1995; Feldman & Singh, 2006; Feldman et al., 2013; Hoffman & Richards, 1984; Koffka, 1935/1965; Leyton, 1989, 1992; Mark, Shaw, & Pittenger, 1988; Mark & Todd, 1985; Ons & Wagemans, 2011; Pittenger & Shaw, 1975; Shaw & Pittenger, 1977).

Understanding and inferring shape-transforming processes presumably involves both perceptual and cognitive abilities. Here, we sought to investigate a specific role that perceptual organization processes play in structuring these inferences. In particular, we suggest that one key component lies in computing how locations on objects shift in space as a result of the transformation. Intuitively, to estimate how points are affected by a transformation, the visual system simply has to identify features on the shape that match up across the transformation (Fig. 1).

However, in practice, identifying such features with arbitrary objects, and then estimating dense correspondence for intervening locations is computationally extremely challenging (Fischer & Modersitzki, 2008; Oliveira & Tavares, 2014). Even computer algorithms that are good at establishing point (location) correspondences across non-rigid transformations (e.g., Ma, Zhao, & Yuille, 2016; Movahedi & Elder, 2010; Myronenko & Song, 2010) eventually fail on images that we find intuitively easy to understand (Fig. 2). Moreover, these algorithms generally involve slow and costly iterative computations, and are fragile, often requiring manual parameter tweaking to achieve optimal results for a given shape and transformation. Furthermore, such algorithms are designed for identifying correspondences between features located on the object itself, but do not usually infer how arbitrary points in space are affected by the transformation. This contrasts with the apparent robustness and flexibility of the human visual system in solving these tasks, which we demonstrate here.

Indeed, the subjective ease with which we tend to solve such problems belies their underlying difficulty, and is only loosely related to transformation complexity. For example, mathematically 'simple' transformations like reflections are not necessarily perceptually simpler to solve (e.g., Gregory & McCloskey, 2010), while at the same time, we seem to be extremely robust at distinguishing causally significant shape features from those that are due to noise, which is a computationally challenging

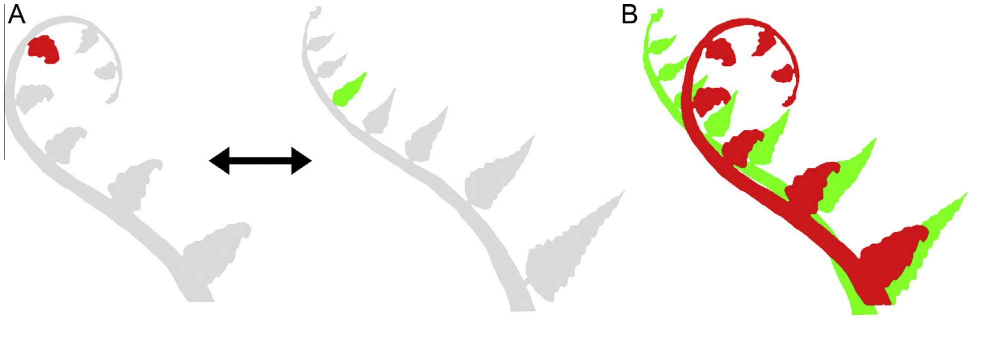

Fig. 1. (A) Example of intuitive matching of shape features across non-rigid transformation (i.e., uncoiling of a fern). (B) Superimposed shapes show that this correspondence cannot be established by simple template mapping.