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Heuristics from Statistics—Modeling the Behavior and Perception of Non-Rigid Materials

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Non-rigid materials, such as jelly or rubber, move and deform in response to external forces. How an object behaves depends on both its internal properties (elasticity, stiffness), and also on external factors, so to estimate material properties the visual system must disentangle several distinct contributions to a given image. For this purpose, it may rely on heuristic visual cues—key features that are broadly diagnostic of a given property, and fairly stable across variations of external factors. Previously we found the magnitude of shape deformation correlates strongly with the stiffness of objects and can predict their apparent softness (Paulun et al., 2017). Here, we focus on visual cues related to the object's motion:

I. Stiffness estimates from internal motion

Stimuli were 25 animations (1s) of an elastic cube set in motion by being prodded by an invisible rod (**Figure 1**). Stiffness of the cube and the strength of the impact were varied in 5 steps each. 12 Participants rated the cubes from soft to hard. Results suggest that perceived softness was mainly determined by the stiffness of the cube, but also influenced by how much it was deformed by the external force.

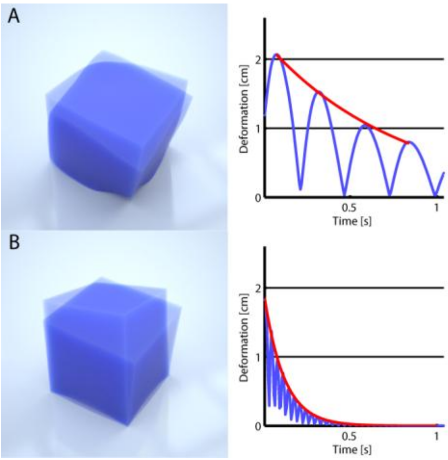

Fig.1: *Example stimuli (overlay of two frames) for an object with low (A) and high (B) stiffness (left) and their characteristic oscillating pattern of deformation (blue) and fitted decay function (red).*

Analysis of the underlying 3D meshes revealed characteristic motion patterns within the objects (**Figure 1**). The deformation of the cubes over time followed a damped oscillation pattern that can be well described by its *fundamental frequency*, *amplitude* and *decay*.

Without any fitting to the data, a simple linear combination of these three factors shows high correlation with perception (r = .94), see **Figure 2.** Thus, the visual system may use the characteristic internal reverberating motion as a cue to an object's stiffness.

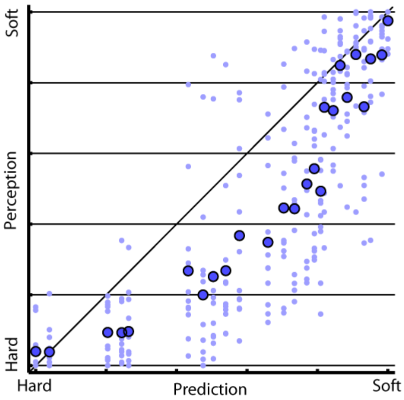

Fig. 2: *Perceived vs. predicted appearance of the cube in all 25 conditions. Large dots show the average, small dots show data of individual participants.*

II. Elasticity estimates from external motion

We simulated 100 000 variations of an object bouncing in a room. Elasticity of the object was varied systematically in ten steps; its initial position, rotation and velocity were varied randomly. We rendered 2 sec of 30 random samples, see **Figure 3**, and observers rated the cube's elasticity. Results suggest that the true elasticity is the major determinant of perceived elasticity, but it is also influenced by external factors.

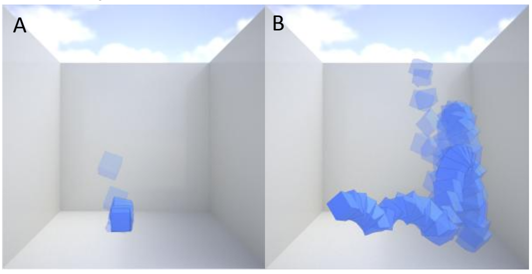

Fig.3: *Low (A) and high (B) elasticity examples (overlay of all frames).*

Analysis of the trajectories of the objects in all simulations revealed characteristic differences in the motion patterns, e.g. the duration of the motion, see **Figure 4**. The pattern of perceptual results is consistent with simple heuristics related to those characteristics.

Investigating the large data set of simulations with unsupervised learning algorithms showed that such heuristics can be derived from the regularities in the behavior of bouncing objects. Indeed an elasticity-like parameter emerges as a variable that accounts for variations between trajectories.

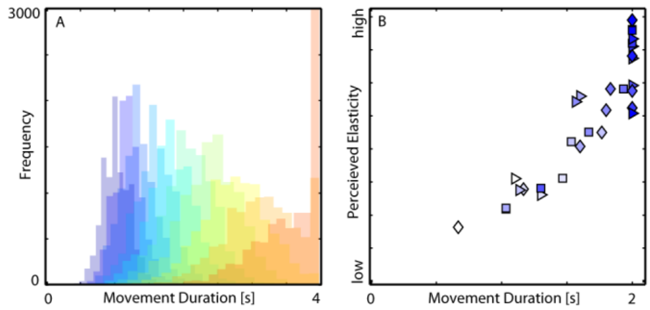

Fig.4: *Histogram (A) of movement duration for objects with different elasticities, color-coded from low (blue) to high (red). The clear relation between movement duration and elasticity is also present in perception (B): longer movements are perceived as more elastic, irrespective of the true elasticity (color-coded from low (light) to high (dark)). Different symbols represent different random samples.*

In sum, the visual system may use simple heuristics related to internal and external motion patterns to estimate the properties of non-rigid objects. Such heuristics could be represented in a data-driven internal model of typical behavior: the closer a given sample is to the signature behavior of that material, the better the estimate. This representation might be derived from observations during development, through exposure to the statistical regularities in the environment.