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Multimodal similarity and categorization of novel, three-dimensional objects

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Abstract

Similarity has been proposed as a fundamental principle underlying mental object representations and capable of supporting cognitive-level tasks such as categorization. However, much of the research has considered connections between similarity and categorization for tasks performed using a single perceptual modality. Considering similarity and categorization within a multimodal context opens up a number of important questions: Are the similarities between objects the same when they are perceived using different modalities or using more than one modality at a time? Is similarity still able to explain categorization performance when objects are experienced multimodally? In this study, we addressed these questions by having subjects explore novel, 3D objects which varied parametrically in shape and texture using vision alone, touch alone, or touch and vision together. Subjects then performed a pair-wise similarity rating task and a free sorting categorization task. Multidimensional scaling (MDS) analysis of similarity data revealed that a single underlying perceptual map whose dimensions corresponded to shape and texture could explain visual, haptic, and bimodal similarity ratings. However, the relative dimension weights varied according to modality: shape dominated texture when objects were seen, whereas shape and texture were roughly equally important in the haptic and bimodal conditions. Some evidence was found for a multimodal connection between similarity and categorization: the probability of category membership increased with similarity while the probability of a category boundary being placed between two stimuli decreased with similarity. In addition, dimension weights varied according to modality in the same way for both tasks. The study also demonstrates the usefulness of 3D printing technology and MDS techniques in the study of visuohaptic object processing.

Keywords: Similarity; Categorization; Multisensory; Haptics; MDS

The question of whether similarity can provide a theoretical basis for general categorization behaviour has been a source of heated debate in the field of cognitive psychology (Goldstone, 1994; Hahn & Ramscar, 2001). Critics of this idea have argued that the notion of similarity is vague and context-dependent, that it cannot explain category coherence, and that it does not account for the important role of theoretical knowledge in categorization decisions (Murphy & Medin, 1985). Nonetheless, similarity has served as the basis for a number of influential models of categorization (Medin & Schaffer, 1978; Nosofsky, 1992; Rosch & Mervis, 1975), which have been particularly successful in explaining classification of perceptual stimuli, including novel, 3D objects (Edelman, 1999). However, much of this work has been carried out within the context of perception involving a single modality, usually vision. Considering similarity and categorization within a multimodal context opens up a number of important questions: Are the similarities between objects the same when they are perceived using different modalities or by more than one modality at a time? Is similarity still able to explain categorization performance when objects are experienced multimodally?

In a preliminary study (Cooke, Steinke, Wallraven, & Bülthoff, 2005), we showed how multidimensional scaling (MDS) techniques can be used to quantify differences in perceptual similarities when objects are perceived using touch and vision. In that study, subjects saw or touched novel, 3D objects which varied parametrically in shape and texture and then rated the similarity between object pairs. Using similarity as a psychological distance measure, MDS was used to visualize stimuli as points in multidimensional perceptual spaces, as, for example, in Shepard and Cermak (1973), Garbin (1988), and Hollins, Faldowski, Rao, and Young (1993). We found that the relative importance of shape and texture in these perceptual spaces differed according to modality: shape alone sufficed to represent

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the stimuli when perceived visually, while shape and texture were both required when the stimuli were perceived haptically.

In the present study, we extend this line of research by adding a second task, free sorting categorization, and including a condition in which objects are simultaneously both seen and touched. The categorization task was included in order to test whether a connection between similarity and categorization could be established within this multimodal context. The bimodal condition was added in order to assess whether multimodal similarity and categorization would be dominated by one specific modality. At first glance, vision appears to be the most likely candidate. Vision is traditionally considered to be the "dominant" modality (Rock & Victor, 1964). Furthermore, object shape has been shown to play a special role in category formation (Landau & Leyton, 1999; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976) and shape is thought to be a particularly salient feature for vision (Klatzky, Lederman, & Reed, 1987). On the other hand, recent studies have challenged the notion of ubiquitous visual capture and have argued in favour of weighted averaging models (Ernst & Bülthoff, 2004; Guest & Spence, 2003).

The results of this study show an effect of modality on the relative importance of object properties for both similarity and categorization tasks. In the bimodal condition, shape and texture were weighted roughly evenly for both tasks, rejecting the visual capture hypothesis. The probability of objects being grouped together in a category increased with similarity, while the probability of a category boundary being placed between two stimuli decreased with similarity. In addition, the relative importance of dimension weights for similarity and categorization tasks varied in the same way as a function of modality. The connection between similarity and categorization in the context of visuo-haptic object processing is discussed in light of these findings.

1. Methods

This section describes the stimulus set, the psychophysical tasks, and the analysis techniques used in this study.

1.1. Stimuli

A family of 25 novel, 3D objects (Fig. 1) was designed using the graphics package 3D Studio Max (3DS). The "base object" in the family (Fig. 1, object 1) consists of three parts connected to a centre sphere, specifying its macrogeometrical structure ("shape") and a displacement map applied to this 3D mesh, specifying its microgeometrical structure ("texture"). The remaining family members were created by parametrically varying the macrogeometrical and/or microgeometrical smoothness of the base object. Macrogeometrical smoothing was accomplished by applying a mesh relaxation operator which locally averages angles in the mesh in five linearly increasing steps (before application of the texture displacement). Microgeometrical smoothing was performed by linearly decreasing the amount of mesh displacement allowed by the application of the texture map in five steps. It is important to understand that the specific values of these parameters are only meaningful within 3DS. In addition, one cannot assume that equidistant changes in a software parameter yield perceptually equidistant changes in object properties.

Once an object is created in 3DS, it can either be rendered into a 2D image or printed into a solid 3D model. Printing is performed by a rapid prototyping machine (Dimension 3D Printer, Stratasys, Minneapolis, USA). The manufacturing process involves a head which deposits filaments of heated plastic such that the model is built up layer by layer. The final result is a hard, white, opaque, plastic model. In our case, models weighed about 40 g each and measured 9.0 ± 0.1 cm wide, 8.3 ± 0.2 cm high, and 3.7 ± 0.1 cm deep. It took 2–4 h to print each object. The same set of 3D models was used in all experiments described below.

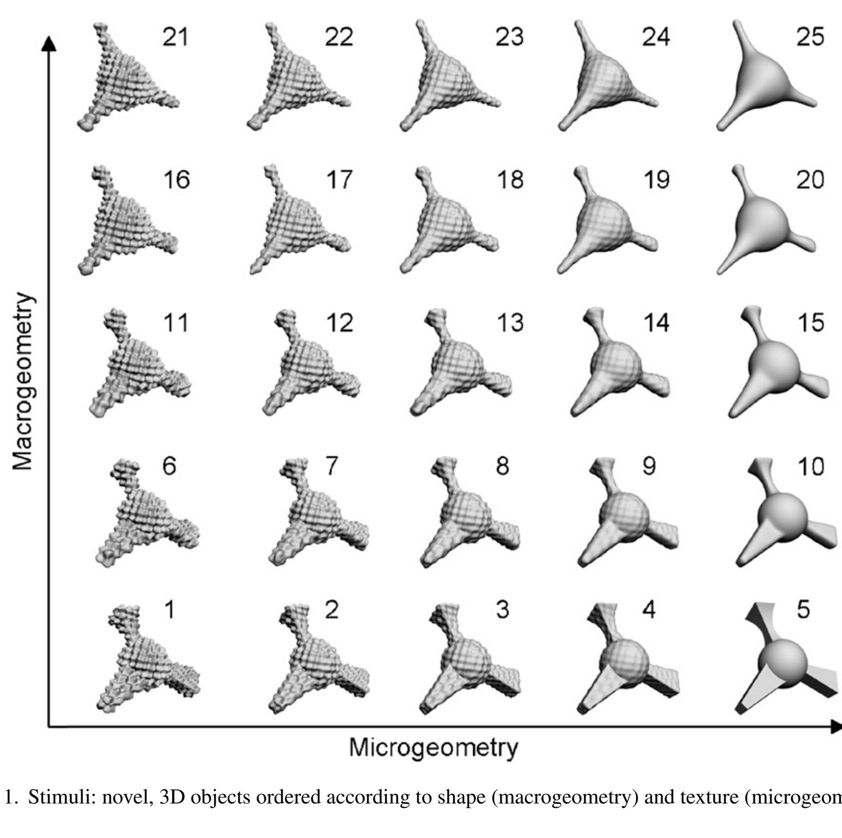

Fig. 1. Stimuli: novel, 3D objects ordered according to shape (macrogeometry) and texture (microgeometry).