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Categorization training increases the perceptual separability of novel dimensions

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ABSTRACT

Perceptual separability is a foundational concept in cognitive psychology. A variety of research questions in perception – particularly those dealing with notions such as "independence," "invariance," "holism," and "configurality" – can be characterized as special cases of the problem of perceptual separability. Furthermore, many cognitive mechanisms are applied differently to perceptually separable dimensions than to non-separable dimensions. Despite the importance of dimensional separability, surprisingly little is known about its origins. Previous research suggests that categorization training can lead to learning of novel dimensions, but it is not known whether the separability of such dimensions also increases with training. Here, we report evidence that training in a categorization task increases perceptual separability of the category-relevant dimension according to a variety of tests from general recognition theory (GRT). In Experiment 1, participants who received pre-training in a categorization task showed reduced Garner interference effects and reduced violations of marginal invariance, compared to participants who did not receive such pre-training. Both of these tests are theoretically related to violations of perceptual separability. In Experiment 2, participants who received pre-training in a categorization task showed reduced violations of perceptual separability according to a model-based analysis of data using GRT. These results are at odds with the common assumption that separability and independence are fixed, hardwired characteristics of features and dimensions.

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1. Introduction

An important task of perceptual systems is to produce a re-description of the incoming sensory input, through a representation that is useful for the tasks that are usually encountered in the natural environment. One way to characterize internal stimulus representations is to determine whether a set of "privileged" stimulus properties exists, which can be used to describe a variety of stimuli, and that are processed and represented independently from one another. In perceptual science, an important amount of effort has been dedicated to understanding what aspects of stimuli are represented in such an independent fashion (e.g., Bruce & Young, 1986; Haxby, Hoffman, & Gobbini, 2000; Kanwisher, 2000; Op de Beeck, Haushofer, & Kanwisher, 2008; Stankiewicz, 2002; Ungerleider & Haxby, 1994; Vogels, Biederman, Bar, & Lorincz, 2001).

There are many different conceptual and operational definitions of what it means for two stimulus dimensions to be independent (Ashby & Townsend, 1986), but perhaps the most widely studied and influential type of independence is dimensional separability. Separable stimulus dimensions are those that can be selectively attended and that directly determine the similarity among stimuli

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(Garner, 1974; Shepard, 1991). This is in contrast to integral dimensions, which cannot be selectively attended and do not directly determine the similarity among stimuli. When stimuli vary along integral dimensions, their similarity is directly perceived and the notion of dimensions loses meaning.

There are two main reasons to believe that a complete understanding of complex forms of visual cognition, such as object recognition and categorization, will benefit from a good understanding of perceptual separability. The first reason is that many important questions in perceptual science can be understood as questions about perceptual separability of object dimensions.

For example, in the area of visual object recognition, the question of whether object representations are invariant across changes in identity-preserving variables (such as rotation and translation; for reviews, see Biederman, 2001; Kravitz, Vinson, & Baker, 2008; Peissig & Tarr, 2007) is essentially the same as the question of whether object representations are perceptually separable from such variables. Shape dimensions that may be important for invariant object recognition have been shown to be separable from other shape dimensions and from viewpoint information, according to traditional tests of separability (Stankiewicz, 2002).

A second example comes from the area of face perception. It has been proposed that a hallmark of human face perception is that faces are processed in a configural or holistic manner (for reviews, see Farah, Wilson, Drain, & Tanaka, 1998; Maurer, Grand, & Mondloch, 2002; Richler, Palmeri, & Gauthier, 2012). Configural or holistic face perception can be seen as non-separable processing of different face features (e.g., Mestry, Wenger, & Donnelly, 2012; Richler, Gauthier, Wenger, & Palmeri, 2008; Thomas, 2001). Similarly, influential theories of face processing have proposed that different aspects of faces, such as identity and emotional expression, are processed independently (e.g., Bruce & Young, 1986; Haxby et al., 2000) and these hypotheses are usually investigated using tests of perceptual separability (e.g., Fitousi & Wenger, 2013; Ganel & Goshen-Gottstein, 2004; Schweinberger & Soukup, 1998; Soto, Musgrave, Vucovich, & Ashby, 2015).

Casting such research questions in terms of perceptual separability is not only possible, but desirable. As we will see below, perceptual separability has a precise formal definition within multidimensional signal detection theory (Ashby & Townsend, 1986; for a review, see Ashby & Soto, 2015), which offers the advantage of providing strict definitions to rather ambiguous concepts such as independence, holistic processing, configural processing, etcetera (e.g., Fitousi & Wenger, 2013; Mestry et al., 2012; Richler et al., 2008). Furthermore, it allows us to determine whether behavioral evidence of a dimensional interaction is due to true perceptual interactions versus interactions at the level of decisional processes.

The fact that a variety of research questions in visual cognition can be characterized as special cases of the problem of perceptual separability suggests that a better understanding of this general problem, including explanations of why some dimensions are separable and how they acquired such status, would necessarily lead to a better understanding of each of the special cases.

A second reason why an understanding of perceptual separability is important to understand visual cognition is that considerable evidence suggests that higher-level cognitive mechanisms are applied differently when stimuli differ along separable dimensions rather than along integral dimensions. Given the definition of perceptual separability, the most obvious of such mechanisms is selective attention, which is more easily deployed to separable than to non-separable dimensions (e.g., Garner, 1970, 1974; Goldstone, 1994b). Other examples of processes that might be applied differently to separable-dimension and integral-dimension stimuli are the rules by which different sources of predictive and causal knowledge are combined (Soto, Gershman, & Niv, 2014), as well as the performance cost of storing an additional object in visual working memory (Bae & Flombaum, 2013).

There is much evidence suggesting that the mechanisms used by people to categorize stimuli vary depending on whether or not categories differ along separable dimensions. Some of this evidence comes from studies using unsupervised categorization tasks, in which people are asked to group stimuli in two or more categories without feedback about their performance. When stimuli in unsupervised categorization tasks vary along separable dimensions, people rely almost exclusively on one-dimensional strategies (Handel & Imai, 1972; Handel, Imai, & Spottswood, 1980; Medin, Wattenmaker, & Hampson, 1987), even in tasks in which categories are not defined by a simple one-dimensional rule and after being explicitly told that the optimal strategy is to integrate information from two dimensions (Ashby, Queller, & Berretty, 1999). Furthermore, unsupervised learning is possible only when the categories clearly differ along a single dimension (Ashby et al., 1999). On the other hand, when stimuli vary along integral dimensions, people show limited ability to learn unsupervised categories and they do not show a strong preference for one-dimensional rules. Instead, they show a variety of strategies, including integration of information from both dimensions (Ell, Ashby, & Hutchinson, 2012).

A similar pattern of results is found in supervised categorization tasks, in which categorization choices are followed by feedback. When stimuli vary along separable dimensions, learning a category structure in which good performance requires attending to a single dimension is much easier for people than learning an equivalent category structure in which good performance requires integration of information from two dimensions (e.g., Smith, Beran, Crossley, Boomer, & Ashby, 2010). There is a large body of evidence suggesting that the one-dimensional categorization task is learned through a rule-based categorization system, whereas the information-integration task is learned through a separate procedural categorization system (for reviews, see Ashby & Maddox, 2005; Ashby & Valentin, 2005). On the other hand, when stimuli vary along integral dimensions, a one-dimensional task is not consistently easier to learn than an information-integration task (Ell et al., 2012).

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