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Level and mechanisms of perceptual learning: Learning first-order luminance and second-order texture objects

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Abstract

Perceptual learning is an improvement in perceptual task performance reflecting plasticity in the perceptual system. Practice effects were studied in two object orientation tasks: a first order, luminance object task and a second-order, texture object task. Perceptual learning was small or absent in the first-order task, but consistently occurred for the second-order (texture) task, where it was limited to improvements in low external noise conditions, or stimulus enhancement [Dosher, B., & Lu, Z. -L. (1998). Perceptual learning reflects external noise filtering and internal noise reduction through channel reweighting. *Proceedings of the National Academy of Sciences of the United States of America*, *95* (23) 13988–13993; Dosher, B., & Lu, Z. -L. (1999). Mechanisms of perceptual learning. *Vision Research*, *39* (19) 3197–3221], analogous to attention effects in first- and second-order motion processing [Lu, Z. -L., Liu, C. Q., & Dosher, B. (2000). Attention mechanisms for multi-location first- and second-order motion perception. *Vision Research*, *40* (2) 173–186]. Perceptual learning affected the later, post-rectification, stages of perceptual analysis, possibly localized at V2 or above. It serves to amplify the stimulus relative to limiting internal noise for intrinsically noisy representations of second-order stimuli.

Keywords: Perceptual learning; Mechanisms of perceptual learning; Stimulus enhancement; Internal noise reduction; First-order luminance system; Second-order texture system

1. Introduction

Perceptual learning, or the improvements in performance with training or practice, is virtually ubiquitous in perceptual tasks. In this paper, we examine and contrast perceptual learning in the domains of first-order (luminance) stimuli and second-order (texture) stimuli. The task is a simple one—discriminating the orientation (right- or left-pointing) of letter objects at fovea. Perceptual learning in these tasks was assessed through measuring contrast thresholds in an external noise paradigm. A perceptual template model (PTM) of the observer distinguishes between mechanisms of perceptual learning—when it occurs—that reflect learned amplification of the stimulus and learned retuning to exclude external noise in the stimulus. Perceptual learning differs profoundly for the comparable tasks using luminance and texture stimuli, implying a higher, post-rectification, level of perceptual learning for this second-order character orientation task.

1.1. Perceptual learning

Perceptual learning has been demonstrated in a wide range of visual judgments in many different task domains, including detection or discrimination of visual gratings (DeValois, 1977; Fiorentini & Berardi, 1980, 1981; Mayer, 1983), stimulus orientation judgments (Dosher & Lu, 1998; Shiu & Pashler, 1992;Vogels & Orban, 1985), motion direction discrimination (Ball & Sekuler, 1982, 1987; Ball,

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Sekuler, & Machamer, 1983), texture discrimination (Ahissar & Hochstein, 1996; Karni & Sagi, 1991, 1993), time to perceive random dot stereograms (Ramachandran & Braddick, 1973), stereoacuity (Fendick & Westheimer, 1983), hyperacuity and vernier tasks (Beard, Levi, & Reich, 1995; Bennett & Westheimer, 1991; Fahle & Edelman, 1993; Kumar & Glaser, 1993; McKee & Westheimer, 1978; Saarinen & Levi, 1995), and object recognition (Furmanski & Engel, 2000), see (Dosher & Lu, 1999b; Fine & Jacobs, 2000) for reviews.

However, the nature and magnitude of perceptual learning may depend upon the level or complexity of the task (Fine & Jacobs, 2002) and the eccentricity or noisiness of the tests (Lu & Dosher, 2004). In certain tasks and conditions, perceptual learning may not occur at all (Herzog & Fahle, 1997; Lu & Dosher, 2004). The limits of perceptual performance and the malleability of these limits with perceptual learning may be different in distinct tasks, and may reflect distinct mechanism(s) of learning. These properties, in turn, will point to the neural substraits of perceptual computations, and inform us about different classes of plasticity in each task domain. The goal is to understand the circumstances under which learned plasticity is possible and to relate these observations to known brain systems and representations. Studying perceptual learning in first- and second-order systems may inform us about the locus and system of learning in the two tasks.

1.2. First- and second-order systems

The distinction between first- and second-order systems has been important in the domains of visual motion perception (Cavanagh & Mather, 1989; Chubb & Sperling, 1989; Lu & Sperling, 1995, 2001b; Sperling, Chubb, Solomon, & Lu, 1994) and in pattern and texture perception(Chubb & Sperling, 1988; Sutter & Graham, 1995), and object perception (Regan, 2000). The first-order visual system operates directly on luminance representations while the second-order visual system operates on pre-processed (i.e., rectified) representations to which the first-order system is blind. The visual system is exquisitely sensitive to luminance patterns and to luminance inputs to motion systems, whereas second-order texture inputs to motion or pattern systems are often characterized by reduced sensitivity (Lu & Sperling, 2001b). Proposed systems for the processing of texture patterns (Regan, 2000; Sutter & Graham, 1995; Wilson, Ferrera, & Yo, 1992) share formal properties with the systems for processing second-order motion (Chubb & Sperling, 1989; Lu & Sperling, 2001a, 2001b; Solomon & Sperling, 1995). In the proposed systems, luminance stimuli are processed through a system of first-order linear filters, often characterized as a bank of spatial-frequency and temporal frequency filters typical of computations in V1 (Fig. 1A). Processing of second-order texture stimuli is generally modeled as a second pathway with a "sandwich" process in which a point-wise non-linearity such as rectification (or half-rectification and pooling, segregating and then combining positive and negative) is carried out between the initial processing by linear filters and subsequent linear filtering (Fig. 1B). This second stage of the pathway has been associated with computations at V2 or above (Lin & Wilson, 1996), where cells selectively responsive to texture or orientation boundaries, but not carrier elements have been reported (von der Heydt, Peterhas, & Baumgartner, 1984), but see (Chaudhuri & Albright, 1977). The second-order (non-Fourier) pathways exhibit characteristically higher (1.4–3×) discrimination thresholds and require longer presentation durations (Lin & Wilson, 1996). Within this framework, perceptual learning may take place at different stages of the processing system reflected in first-order and second-order stimuli and tasks.

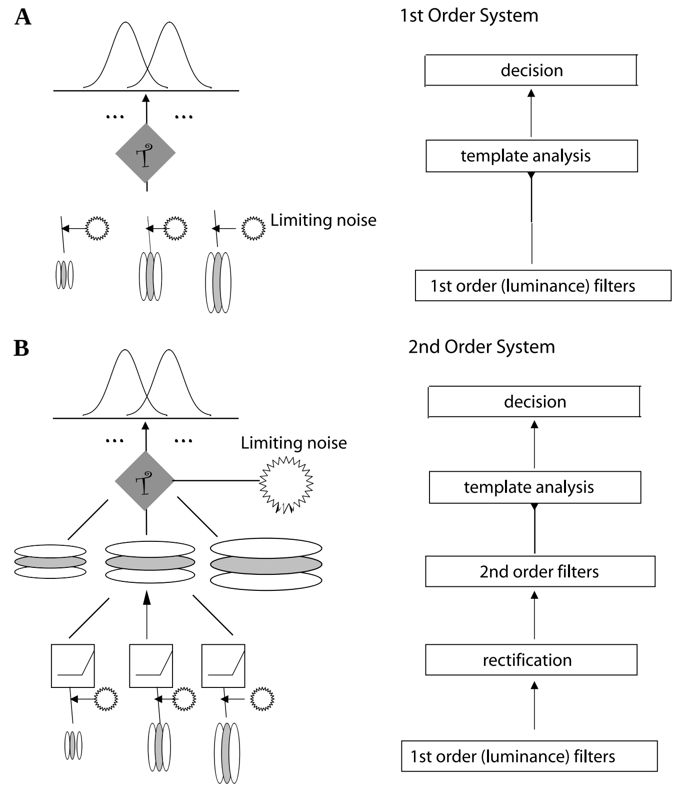

Fig. 1. A schematic two-level architecture for analysis of second-order task processing. First-order tasks could be based on an initial Fourier channels, consistent with analysis at V1, while second-order tasks are based on rectified representations, consistent with analysis at V2 or higher.

Comparing perceptual learning in analogous first- and second-order letter orientation tasks will have implications for the localization of the learning in the first- and second-order systems. Moreover, if perceptual learning occurs for either task, the mechanism of the learning (stimulus enhancement or external noise exclusion, see Section 1.4) can be identified through external noise studies. Learning in the second-order task in the absence of learning in the comparable first-order task would suggest that perceptual learning occurs in the second (post-rectification) stages of the non-Fourier pathways, at the level of V2 or above. If