Cognition 135 (2015) 24–29

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Fitting perception in and to cognition

Robert L. Goldstone [*], Joshua R. de Leeuw, David H. Landy

Indiana University, Department of Psychological and Brain Sciences, Program in Cognitive Science, 1101 E. 10th Street, Bloomington, IN 47405, United States

ARTICLE INFO

Article history:
Available online 8 December 2014

Keywords:
Perceptual learning
Categorical perception
Modularity
Cognitive penetrability
Cognition
Perception

ABSTRACT

Perceptual modules adapt at evolutionary, lifelong, and moment-to-moment temporal scales to better serve the informational needs of cognizers. Perceptual learning is a powerful way for an individual to become tuned to frequently recurring patterns in its specific local environment that are pertinent to its goals without requiring costly executive control resources to be deployed. Mechanisms like predictive coding, categorical perception, and action-informed vision allow our perceptual systems to interface well with cognition by generating perceptual outputs that are systematically guided by how they will be used. In classic conceptions of perceptual modules, people have access to the modules' outputs but no ability to adjust their internal workings. However, humans routinely and strategically alter their perceptual systems via training regimes that have predictable and specific outcomes. In fact, employing a combination of strategic and automatic devices for adapting perception is one of the most promising approaches to improving cognition.

1. Introduction

Attempts to describe the interface between perception and cognition presume that perception and cognition can be separated from one another. It only makes sense to talk about the interface between processes A and B if they are, in fact, two separate, albeit linked, processes. Given the difficulties in sharply delineating between perception and cognition, some thinkers have been led to the radical move of completely lumping them together. With the notion of perception as unconscious inference, Helmholtz (1867) joined perception and cognition, with both crucially involving the interpretation of the world. The Buddhist mental factor Saṃjñā has been translated alternatively as "cognition" or "perception." Talmy (2000) advocated using the term "ceptions" to purposefully merge perception and conception, motivated by an effort to break down artificial boundaries between these mental acts. More recently, Clark (2013) has argued that "the lines between perception and cognition [are] fuzzy, perhaps even vanishing" (p. 190).

2. Adaptive perceptual modules

Still, there are good reasons to prefer construing perception and cognition as interactive, even overlapping, processes, but nonetheless differentiated. The brain is comprised of anatomically localized regions with relatively dense within-region neural connectivity and sparser between-region connectivity. Brain regions can often times be attributed specific perceptual tasks, such as the perception of color, binocular depth perception, reading, and face recognition. The articulation of the brain into modules such as these is crucial for achieving fast and reliable perception (Nakayama, 2005). Cases of cognitive impenetrability exist in which particular goals, expectations, and beliefs one has do not influence one's perception (Pylyshyn, 2003). More generally, there is a theoretical advantage to conceptualizing most active agents embedded in environments in terms of perception, cognition, and action. For extended and embedded agents from cars

---

[*] Corresponding author. Tel.: +1 812 855 4853.
E-mail address: rgoldsto@indiana.edu (R.L. Goldstone).

http://dx.doi.org/10.1016/j.cognition.2014.11.027

to people to webpages to aircraft carriers, it is useful to think of some components playing primarily information processing roles, and some as primarily processing the specific nature of the environmental information. Our conceptualization of conceptualization itself should not become so blended with perception that the evidence for and conceptual advantages of partially independent perceptual modules are lost.

Granting the existence of perceptual modules does not commit one to the assumption that these modules are hardwired or fixed in their function. In fact, perceptual modules are highly adaptive and become attuned across several temporal scales to the cognitive needs of an organism. At the longest, evolutionary time scale, organisms evolve perceptual systems that are tailored to their stable environment. A compelling case of this is the close match between the peak light wavelength sensitivity of photoreceptors in fish to the most prominent wavelengths in their water environments (Lythgoe, 1972). At the intermediate time scale of learning throughout an organism's lifetime, perceptual modules become tuned to frequently recurring patterns. At the most rapid time scale of moment-to-moment changes in context, responses in our earliest perceptual systems become modified by expectancies (Lupyan & Ward, 2013). For example, training in a selective attention task produces differential responses as early as the cochlea (Puel, Bonfils, & Pujol, 1988). This amazing degree of top-down modulation of a peripheral neural system is mediated by descending pathways of neurons that project from the auditory cortex all the way back to olivocochlear neurons, which directly project to outer hair cells within the cochlea—an impressively peripheral locus of modulation.

Perceptual learning over the course of an organism's lifetime is a particularly powerful way of altering the functioning of perceptual modules so that they come to better serve an organism's cognitive needs. Even if humans are not consciously and strategically changing the "wiring" of perceptual modules (a possibility we will return to later), these modules nonetheless adapt systematically at the time scales of tens to thousands of repetitions to allow an organism to better make discriminations and categorizations that are vital to its interests. Empirical evidence points to neurophysiological changes to properly perceptual, rather than post-perceptual decision, brain regions. For example, when monkeys are trained with one of two visual discrimination tasks (a bisection task or vernier discrimination), their primary visual cortex (V1) neurons take on different novel function properties pertinent to these tasks even when presented with the same shape (Wu, Piëch, & Gilbert, 2004). These V1 differences are observable from the very earliest neural responses following stimulus onsets. Generalizing over many studies, training in both auditory and visual tasks produces early changes to many perceptual modules. One of the mechanisms for these changes are that neurons become more selective in their responses and the cortical representations of different features become increasingly less overlapping (Crist, Li, & Gilbert, 2001).

This evidence from neuroplasticity apparently clashes with epistemological concerns about perceptual systems being "tainted" by preconceptions. The concern is that if our perception of the world depends on our experiences and wishes, then how can these perceptions then provide us with unbiased evidence about the world (Siegel, 2012)? As Fodor (1983) puts it: "seeing what we expect seems to defeat the purpose of vision: [an organism] generally sees what's there, not what it wants or expects to be there. Organisms that don't do so become deceased" (p. 68). Hallucination is counterproductive.

The resolution to this apparent clash is that there is good reason to suspect that hallucination is in fact minimized when our perceptions *are* influenced by our cognitive requirements (Lupyan, in press). These requirements, again, will reflect evolutionary, life-long, and moment-to-moment needs. Occasionally, the needs of these temporal scales are inconsistent, producing noticeable perceptual effects (Anstis, Verstraten, & Mather, 1998; Barlow, 1990). Yet, on the whole, adaptation of the perceptual system to the demands of cognition increases the efficacy and efficiency of perceptual processing (Benucci, Saleem, & Carandini, 2013; Çukur, Nishimoto, Huth, & Gallant, 2013). The reason for perceptual learning on this view is that the needs of one specific member of a species might differ from other members' needs because of how it is making its idiosyncratic living. A father of identical twins needs to develop an ability to efficiently distinguish them that other people need not, and a radiologist needs to develop the ability to distinguish cancerous tumors from benign tissue at an expert level beyond the needs of most of humanity (Gauthier, Tarr, & Bubb, 2010). Borrowing from Fodor: organisms that waste their time seeing everything that is there, instead of perceiving relative to their expectations and needs, end up dead.

Researchers have described a "hierarchical predictive coding" account in which a cognizing system can have its perceptual encodings affected by its needs and experiences at every step of sensory transformation (Clark, 2013; Friston, 2010). What is perceived is a synthesis of the sensory input as it is best predicted by existing generative models at multiple levels, plus the aspects of the input that have not been successfully predicted by higher-level areas, and are thus providing feedback signals to adapt the generative models. The top-down generated predictions and error from these predictions seem to be represented in different areas (superior temporal sulcus and fusiform face area, respectively, in the case of face stimuli), providing support for this functional decomposition (Apps & Tsakiris, 2013). Although additional support for this approach is still needed, the benefits of a cognitive system that is perceiving inputs relative to its many-leveled expectations are clear, and plausible neural and computational implementations are available (Rao & Ballard, 1999; Spratling, 2008).

3. Making perception pertinent to cognition and action

There are many ways in which cognition and action become intertwined with perceptual processing. Researchers have identified and distinguished attentional orientation (changes in the inputs to the perceptual system, most blatantly, by turning one's head in a particular direction, for example), attentional modulation effects (changing the "gain" on information signals without changing the input), perceptual learning effects (adaptation of the perceptual system over time), and top-down effects of cognition (moment-to-moment changes in perceptual processing as a result of cognitive demands and expectations) (Pylyshyn, 1999). These distinctions are useful for guiding research efforts at pinpointing loci of experiential influences on perception and cognition. However, these distinctions also risk neglecting the interactive nature of these processes. We alter our behavior in response to cognitive demands, and as a result, change the input to the perceptual system. Changes in the inputs to the perceptual system will alter what the perceptual system adapts to through perceptual learning, which in turn will affect cognition.

The phenomenon of categorical perception (CP) is a good example of how perception comes to better interface with cognition by leading us to perceive our world in terms of the categories that we have formed (Goldstone & Hendrickson, 2010). By CP, our perceptions are warped such that differences between objects that belong in different categories are accentuated, and differences between objects that fall into the same category are deemphasized (Harnad, 1997). CP occurs for learned visual (Goldstone, 1994) and auditory (Pisoni, Aslin, Perey, & Hennessy, 1982) categories, and transforms relatively linear sensory signals into relatively nonlinear internal representations. This transformation is important because it promotes the crucial cognitive function of treating distinguishable stimuli as the same thing. Once different examples of a phoneme/d/, different cats, or different chairs are treated as the same kinds of thing, then irrelevant variations are deemphasized and connections can be made between things that have disparate superficial appearances. While we might have expected these connections to be made only at deeper, cognitive levels, turning over some of the work in creating equivalence classes to perceptual systems frees up executive control functioning for other tasks and leads to the fast and efficient detection of categories.

There are other striking examples of visual processes being tailored to an organism's tasks. Milner and Goodale (1995) have proposed interacting but distinct visual pathways involved in visual identification/recognition of an object and reaching for that object. One confirmed prediction of the idea that perceptual processes are tuned to the currently relevant actions is that visual systems engaged in identification/recognition and reaching should not always show the same pattern of sensitivity to illusions (Aglioti, DeSouza, & Goodale, 1995; Bruno & Franz, 2009). While verbally reported size judgments for a central circle are heavily influenced by the sizes of surrounding circles, grasps for the central circle are relatively unaffected. This is a plausible pattern if one assumes that successful grasps depend on metric calculations based on the target itself, whereas explicit perceptual judgments about that target can sometimes benefit from determining its relation to other objects (Franz, 2001).

Even more surprising arguments for an influence of an organism's tasks on its perception are that people scale their perceptions of an environment according to their bodily experience writ large, including their energetic state. People who have more energy, because they have drunk a beverage containing glucose, seem to perceive a hill to be less steep than those who have drunk a beverage containing non-caloric sweetener (Schnall, Zadra, & Proffitt, 2010). Likewise, individuals wearing a heavy backpack judge a hill to be steeper than those who are not (Proffitt, 2006). People who can jump higher judge heights to be lower (Lessard, Linkenauger, & Proffitt, 2009). However, these results are controversial (Firestone, 2013) and highlight the difficulty of distinguishing changes in perception from changes in post-perceptual decision-making. Critiques of the work have proposed an alternative account of the results in which participants in these experiments are altering their *report* of what they perceive, as opposed to actually experiencing a perceptual shift (Firestone & Scholl, 2014). Reducing the potential for demand effects – for example, by giving participants a plausible explanation for wearing a heavy backpack to decrease their suspicion/awareness of the experimental manipulation – seems to reduce or eliminate many of these effects, suggesting a non-perceptual locus (Durgin, Klein, Spiegel, Strawser, & Williams, 2012; Shaffer, McManama, Swank, & Durgin 2013).

Other results showing influences of subjective evaluations on distance perception overcome some of these objections by using both explicit and implicit measures of distance perception. For example, Balcetis and Dunning (2010) find that more desirable objects, such as a glass of water when perceivers are thirsty rather than sated, or a gift card worth $25 vs $0, are perceived as being closer than the less desired objects. In addition to measuring distance with explicit length judgments, these effects are also found when participants are asked to throw a bean bag to the object, with underthrows being more common for more desired objects (see also Balcetis, Dunning, & Granot, 2012 for influences of subjective value on dominance in binocular rivalry). The general perspective that an organism's circumstances will influence the specific nature of its perceptual transformations is fertile. It is at least a coherent proposal that systematically distorted perceptual system outputs will serve the needs of an organism better than uninfluenced outputs. For Balcetis and Dunning's perceivers, if desired objects are perceived as closer, then this may automatically dispose them toward approaching the objects. Of course, the more straightforward route of having their desires influence their strategic, conscious decisions to approach objects without affecting perceptual outputs is also plausible. The working hypothesis is that a goal should increasingly affect an agent's perceptual outputs rather decisional stages as the goals recur increasingly often and consistently, as the cost of strategic decision making increases, and when other goals do not put competing pressures on perceptual outputs. Future research will be needed to substantiate whether specific and transitory circumstances can override an organism's broader circumstances, but in any case, a promising way of understanding perception is by understanding what it allows us quite specifically to think and do.

4. Hacking perception for cognition

Thus far, we have argued that part of the reason why perception and cognition interface so well is that perceptual processes adapt to fit our needs for cognition and action. This adaptation often happens without our strategic efforts to shape perception, and some researchers argue that it is the very nature of a module that it cannot be strategically revamped to fit one's needs (Fodor, 1983). In fact, humans are highly resourceful in how they manage to alter perception in order to accomplish tasks (Goldstone, Landy, & Brunel, 2011). Most athletes and musicians are familiar with applying existing, and creating novel, training methods to improve their own performance. For example, soccer players may train themselves in a multiple object tracking task in order to improve their global situation awareness on the field (Faubert & Sidebottom, 2012). Musicians give themselves ear training exercises that specifically allow them to better discriminate troublesome intervals.

If we understand cognitive impenetrability to mean that our perceptual processes are structured such that we have access to their outputs but no ability to adjust their internal workings, then these examples of expert performance are imperfect cases of cognitive penetrability to be sure. Short of autoneurosurgery, people do not have the ability to completely rewire their perceptual systems to give themselves new perceptual capabilities, such as seeing infrared light or hearing a 30 kHz pitch. However, we routinely and strategically modify human perceptual systems by giving ourselves and our students targeted training. Professors of dermatology strategically present their medical students with paired examples of Lichen planus and Psoriasis to help them distinguish these confusable diseases. Very different training is required of music students to master discriminations between absolute pitches (e.g. A vs A#) vs relative intervals (e.g. minor vs major thirds) (Aruffo, Goldstone, & Earn, in press; Hannon & Trainor, 2007), and students regularly avail themselves of training methods suited to their musical goals. Dr. Susan Barry lacked binocular stereoscopic depth perception, but was able to strategically train herself to have this ability by presenting to herself colored beads at varying distances and forcing her eyes to jointly fixate on them (Sacks, 2006). It is worth noting for this last example that binocular depth perception is one of the human perceptual abilities with the strongest empirical claims for having status as a neurophysiologically and functionally genuine module (Nakayama, 2005).

In all of these examples, people are being highly strategic in terms of how they are training their perceptual systems to better serve their needs. Just because lay humans do not (yet) possess an ability to directly alter their own neural circuitry does not mean that they can only resort to random flailing to modify their perceptions. Over the course of our experiences with ourselves, we develop enough introspective leveraging to apply instructions, sequencing, attentional highlighting, caricaturing, task decomposition, repetition, and other learning "hacks" to tailor our perceptual systems in impressively specific ways. More concretely, we also use physical and cultural artifacts to transform the sensory information that trains our neural circuitry. Glasses, telescopes, charts, mathematical notation, and written language all transform the way that external environments trigger our perceptual apparatus, and so strategically alter the training those visual systems receive.

Pylyshyn (1999), Pylyshyn (2003) acknowledges that perceptual learning can result in changes to the outputs of early perceptual systems, but resists interpreting these changes as cases of cognitive penetrability, which he takes as entailing that the content of perception is rationally connected to beliefs, expectations, or values. However, the above cases of willful, strategic training of perception to improve its operation for highly specific purposes highlights the difficulties in cleanly separating rational from non-rational influences. For example, as Susan Barry trained herself to have depth perception, she *wanted* to have depth perception, she *believed* that her training regime would serve to give her this ability, and the training itself was systematically related to her developing the ability. If this does not count as a rational process, then many canonical cases of human rational inference will probably fail to count as well. More generally, studying the cycle of interactions between moment-to-moment goals, strategic training, perceptual learning, regular monitoring of performance, and revision of goals is a promising approach to understanding perception, and one that may prove just as fertile as experimental attempts to cleanly separate attentional, perceptual, and decisional influences of goals and beliefs. This cycle of interactions can often achieve functional hacks to our perceptual systems even without our being able to directly manipulate our neural networks.

Because of the pervasive culturally driven alteration of our environments, our brains are automatically "hacked" to perceive forms that they were never evolved to process. Human brains repurpose a rather specific region (the VWFA) for word perception that was not originally evolved for that purpose (Dehaene et al., 2010). Likewise, the left intraparietal sulcus, associated with the function of shifting attention, has come to be reliably coopted for numerical cognition in numerate modern humans (Dehaene, Molko, Cohen, & Wilson, 2004). Sometimes this repurposing blends cognitive and perceptual functions within anatomically unified regions: the motor cortex seems sometimes to be used for language, sensory-motor regions for finger representations used for mathematics, and spatial processing regions used for higher-level conceptualization (Anderson, 2010). These repurposings provide a mechanism via which high-level and relatively recently acquired cognitive capacities can be grounded in well-entrenched perceptual processes without requiring much change to the original neural circuitry.

Together, these strategic and automatic devices for adapting perceptual systems may be one of the most promising avenues for improving cognition. It is common to think of perception as antithetical to sophisticated cognition. After all, perception can be superficial and misleading, as when we mistake pyrite for real gold or believe that two physics problems that both involve inclined planes should be solved similarly. In these cases, it is tempting to retreat to formal reasoning as the defense against misleading perceptions. However, an alternative approach is to seek out ways of *educating* perceptual systems so that they are brought in closer alignment with the requirements of formal reasoning (Goldstone, Landy, & Son, 2010; Kellman, Massey, & Son, 2010). This is particularly promising because humans have the ability not only to change our perceptual systems, but also alter the formal, symbolic objects that operate on those systems (Changizi & Shimojo, 2005). By adapting our perception, both strategically and automatically, and by adapting our external representations to fit existing perceptual constraints, we become far more sophisticated cognizers than we would have if we forsook our perceptually based insights altogether.

Acknowledgements

This research was supported in part by National Science Foundation REESE Grant No. 0910218 and Department of Education IES Grant No. R305A1100060.

References

Aglioti, S., DeSouza, J. F., & Goodale, M. A. (1995). Size-contrast illusions deceive the eye but not the hand. *Current Biology, 5*, 679–685.

Anderson, M. L. (2010). Neural reuse: A fundamental organizational principle of the brain. *Behavioral and Brain Sciences, 33*, 245–313.

Anstis, S., Verstraten, F. A., & Mather, G. (1998). The motion aftereffect. *Trends in Cognitive Sciences, 2*(3), 111–117.

Apps, M. A. J., & Tsakiris, M. (2013). Predictive codes of familiarity and context during the perceptual learning of facial identities. *Nature Communications, 4*, 2698.

Aruffo, C., Goldstone, R. L., & Earn, D. J. D. (in press). Absolute judgment of musical interval width. Music Perception.

Balcetis, E., & Dunning, D. (2010). Wishful seeing: More desired objects are seen as closer. *Psychological Science, 21*, 147–152.

Balcetis, E., Dunning, D., & Granot, Y. (2012). Subjective value determines initial dominance in binocular rivalry. *Journal of Experimental Social Psychology, 48*, 122–129.

Barlow, H. (1990). A theory about the functional role and synaptic mechanism of visual after-effects. In C. B. Blakemore (Ed.), *Vision: Coding and efficiency* (pp. 363–375). Cambridge University Press.

Benucci, A., Saleem, A. B., & Carandini, M. (2013). Adaptation maintains population homeostasis in primary visual cortex. *Nature Neuroscience, 16*(6), 724–729.

Bruno, N., & Franz, V. H. (2009). When is grasping affected by the Müller-Lyer illusion? A quantitative review. *Neuropsychologia, 47*, 1421–1433.

Changizi, M. A., & Shimojo, S. (2005). Character complexity and redundancy in writing systems over human history. *Proceedings of the Royal Society of London B: Biological Sciences, 272*, 267–275.

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences, 36*(3), 181–204.

Crist, R. E., Li, W., & Gilbert, C. D. (2001). Learning to see: Experience and attention in primary visual cortex. *Nature Neuroscience, 4*, 519–525.

Çukur, T., Nishimoto, S., Huth, A. G., & Gallant, J. L. (2013). Attention during natural vision warps semantic representation across the human brain. *Nature Neuroscience, 16*, 763–770.

Dehaene, S., Molko, N., Cohen, L., & Wilson, A. J. (2004). Arithmetic and the brain. *Current Opinion in Neurobiology, 14*, 218–224.

Dehaene, S., Pegado, F., Braga, L. W., Ventura, P., Nunes Filho, G., Jobert, A., et al. (2010). How learning to read changes the cortical networks for vision and language. *Science, 330*, 1359–1364.

Durgin, F. H., Klein, B., Spiegel, A., Strawser, C. J., & Williams, M. (2012). The social psychology of perception experiments: Hills, backpacks, glucose and the problem of generalizability. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 1582–1595.

Faubert, J., & Sidebottom, L. (2012). Perceptual–cognitive training of athletes. *Journal of Clinical Sports Psychology, 6*, 85–102.

Firestone, C. (2013). How "paternalistic" is spatial perception? Why wearing a heavy backpack doesn't—and couldn't—make hills look steeper. *Perspectives on Psychological Science, 8*, 455–473.

Firestone, C., & Scholl, B. J. (2014). "Top-down" effects where none should be found: The El Greco fallacy in perception research. *Psychological Science, 25*(1), 38–46.

Fodor, J. A. (1983). *The modularity of mind*. Cambridge, MA: MIT Press.

Franz, V. H. (2001). Action does not resist visual illusions. *Trends in Cognitive Sciences, 5*, 457–459.

Friston, K. J. (2010). The free-energy principle: A unified brain theory? *Nature Reviews Neuroscience, 11*, 127–138.

Gauthier, I., Tarr, M. J., & Bubb, D. (Eds.). (2010). *Perceptual expertise: Bridging brain and behavior*. Oxford: Oxford University Press.

Goldstone, R. L. (1994). Influences of categorization on perceptual discrimination. *Journal of Experimental Psychology: General, 123*, 178–200.

Goldstone, R. L., & Hendrickson, A. T. (2010). Categorical perception. *Wiley Interdisciplinary Reviews: Cognitive Science, 1*, 69–78.

Goldstone, R. L., Landy, D., & Brunel, L. (2011). Improving perception to make distant connections closer. *Frontiers in Perception Science, 2*(385), 1–10.

Goldstone, R. L., Landy, D. H., & Son, J. Y. (2010). The education of perception. *Topics in Cognitive Science, 2*, 265–284.

Hannon, E. E., & Trainor, L. J. (2007). Music acquisition: Effects of enculturation and formal training on development. *Trends in Cognitive Sciences, 11*, 466–470.

Harnad, S. (1997). *Categorical perception*. Cambridge: Cambridge University Press.

Helmholtz, H. von (1867/1925). Treatise on physiological optics (from 3rd German edition, Trans.) (3rd ed., Vol. III). New York: Dover Publications.

Kellman, P. J., Massey, C. M., & Son, J. Y. (2010). Perceptual learning modules in mathematics: Enhancing students' pattern recognition, structure extraction, and fluency. *Topics in Cognitive Science, 2*, 285–305.

Lessard, D. A., Linkenauger, S. A., & Proffitt, D. R. (2009). Look before you leap: Jumping ability affects distance perception. *Perception, 38*(12), 1863–1866.

Lupyan, G. (in press). Cognitive penetrability of perception in the age of prediction: Predictive systems are penetrable systems. Review of philosophy and psychology.

Lupyan, G., & Ward, E. J. (2013). Language can boost otherwise unseen objects into visual awareness. *Proceedings of the National Academy of Sciences, 110*(35), 14196–14201.

Lythgoe, J. N. (1972). The adaptation of visual pigments to the photic environment. In H. Dartnall (Ed.), *Handbook of sensory physiology. Part 1: Photochemistry of vision* (Vol. 7, pp. 566–603). Berlin: Springer-Verlag.

Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action*. Oxford, England: Oxford University Press.

Nakayama, K. (2005). Modularity in perception, its relation to cognition and knowledge. In E. B. Goldstein (Ed.), *Blackwell handbook of sensation and perception*. Malden, MA, USA: Blackwell Publishing Ltd.

Pisoni, D. B., Aslin, R. N., Perey, A. J., & Hennessy, B. L. (1982). Some effects of laboratory training on identification and discrimination of voicing contrasts in stop consonants. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 297–314.

Proffitt, D. R. (2006). Embodied perception and the economy of action. *Perspectives on Psychological Science, 1*(2), 110–122.

Puel, J. L., Bonfils, P., & Pujol, R. (1988). Selective attention modifies the active micromechanical properties of the cochlea. *Brain Research, 447*, 380–383.

Pylyshyn, Z. (1999). Is vision continuous with cognition?: The case for cognitive impenetrability of visual perception. *Behavioral and Brain Sciences, 22*(3), 341–365.

Pylyshyn, Z. (2003). *Seeing and visualizing: It's not what you think*. Cambridge, MA: The MIT Press.

Rao, R., & Ballard, D. (1999). Predictive coding in the visual cortex: A functional interpretation of some extra-classical receptive field effects. *Nature Neuroscience, 2*(1), 79–87.

Sacks, O. (2006). A neurologist's notebook, "Stereo Sue", The New Yorker, June 19, p. 64.

Schnall, S., Zadra, J. R., & Proffitt, D. R. (2010). Direct evidence for the economy of action: Glucose and the perception of geographical slant. *Perception, 39*(4), 464–482.

Shaffer, D. M., McManama, E., Swank, C., & Durgin, F. H. (2013). Sugar and space? Not the case: Effects of low blood glucose on slant estimation are mediated by beliefs. *i-Perception, 4*, 147–155.

Siegel, S. (2012). Cognitive penetrability and perceptual justification. *Noûs, 46*(2), 201–222.

Spratling, M. W. (2008). Predictive coding as a model of biased competition in visual attention. *Vision Research, 48*(12), 1391–1408.

Talmy, L. (2000). *Toward a cognitive semantics*. Cambridge, MA: MIT Press.

Wu, L., Piëch, V., & Gilbert, C. D. (2004). Perceptual learning and top-down influences in primary visual cortex. *Nature Neuroscience, 7*, 651–657.