

A Temporal-Difference Model of Perceptual Stability in Color Vision

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Abstract

We consider the problem of how humans can maintain a stable perception of object color across saccades in spite of the changes in sensory input caused by the spatially non-homogeneous receptor spectral sensitivities. We propose a method, based on a temporal-difference reinforcement learning scheme, for constructing associations between pre- and post-motor stimuli and which yields a constant color percept across saccades.

1. Introduction

When humans make self-directed actions, such as body or eye movements, their perception of the world is a stable one. That is, even though their eyes may be moving, and the retinal images may be changing drastically, the external world appears to be stable [2, 6]. The process by which this apparent stability is maintained in the face of wildly varying sensory input has long been a subject of intense debate.

There have been many theories proposed to explain the phenomenon of perceptual stability (see discussion in [2]). One approach is to “compensate” for the retinal image change with the help of proprioceptive information about the motion of the eye. The problem with this approach is that the proprioceptive signals that are actually available are too noisy and imprecise to yield a stable perception. Another popular theory involves the use of a “perceptual buffer” which can hold a detailed, world-centred, representation of the world. Eye position information is used to determine which region of this buffer should be updated with the current retinal

sense data. This theory, however, has not been supported by psychophysical evidence [4] and, as O'Regan [7] points out, a detailed internal representation of the world is unnecessary and wasteful as the visual-motor system can quickly access any needed information by making an appropriate eye movement.

A more promising theory, originally proposed by MacKay [5] is based on the recognition that if the external world is always stable there is no need for its internal representation (if such exists) to ever be updated in response to sensory input. Clearly the external world is not always stable, but one can make an assumption that the external world is always stable during the execution of a self-motion, such as an eye movement. Thus, there will usually be no need to update the representation of the external world in response to the sensory input induced by the self motion, and hence stability will be perceived. Such an explanation for the perceptual stability of object positions across saccadic eye movements has been proposed by McConkie *et al.* [6]. Their theory, which they refer to as the *Saccade Target Theory* hypothesizes that before a saccade is generated, a template of the peripheral saccade target is made. Then, after the saccade is made, the foveal image data is compared with the target template. If there is a significant change, an instability is signaled and appropriate action is taken (e.g. a corrective saccade or updating of the internal world representation).

We propose to generalize the saccade target theory and state that perceptual stability in general arises by learning the effects one's actions have on sensor responses. In fact, one can go further and propose, following O'Regan and Noë [8], that it is precisely the sensory variation contingencies on the motor acts that

comprise the perception, rather than the raw sensor data. Thus, the (proper) variation of sensor data in response to a motor act is a *requirement* for stable perception rather than an indication of instability.

2. Stability of Color Perception

While most researchers in the field of perceptual stability have considered only the stability of the spatial layout of the world [2, 4, 5, 6], there are many forms of non-spatial perceptual stability. In this paper we will examine one of these, the apparent stability of *color perception*.

One of the most striking characteristic of the human visual system is its non-homogeneity. The spatial resolution of the retina is not uniform, but decreases steadily away from the central region, or fovea. The retina also has non-homogeneity in the color sensitivity of the retinal photoreceptors. In the central macular region, there exist three wavelength selective photoreceptor cone classes of which the long and medium wavelength sensitive are most numerous. In the periphery the cones are very sparsely distributed relative to the non-color selective rods. An additional important non-homogeneity arises from the fact that the macular pigment, which is a yellowish jelly that covers the macula, absorbs up to 50% of the light in the short wavelength range [1], causing a significant shift in the color sensitivity of foveal receptors. For small pupil sizes the absorption of the lens material also provides a wavelength dependent attenuation, similar in effect to the macular pigment absorption [12]. For wide pupils incoming light is spread over the lens, so optical path lengths to various points on the retina are more or less the same, and hence the lens absorption effect is more uniform than with narrow pupils.

In spite of these non-homogeneities, the perception of color is remarkably stable across eye positions. We have the subjective impression that the color of an item in the world is the same when viewed peripherally as when viewed foveally. One could hypothesize that this constancy of color vision with varying eye position is due to some compensation scheme that modifies the sensor data depending on the retinal eccentricity of the sensor, in order to provide a constant sensor response at all eccentricities. This compensation is unnecessary, however. Following the sensorimotor-contingencies theory of O'Regan and Noë [8], we propose that the apparent stability of color perception can be explained as an instance of the general mechanism for perceptual stability that we described earlier. That is, color perception is stable because the observers have learned the changes that occur in the sensory input

when eye movements are made, and it is these learned contingencies that comprise the perception, rather than the raw sense data. This approach has the advantage over "compensation" theories of color stability in that it does not require any neural circuitry to compute the compensations.

This is similar to that of McConkie *et al.* saccade target theory, in that color features of the pre-motor peripheral target is attended to and then compared to the post-motor foveal color features. Unlike the McConkie *et al.* theory, however, we propose that the comparison operation is not explicit, but arises out of a learned association between the pre- and post-motor appearances of the saccade target.

3. A Temporal-Difference Model of Perceptual Stability

Our model of trans-saccadic perceptual stability is characterized by a sequence of events associated with an eye movement. First, attention shifts to a peripheral location and features are attentionally selected according to the current visual analysis task. The active features are remembered in a short term memory trace. Next, in accordance with Rizzolatti's *pre-motor* theory of attention [3, 11], a saccade may be generated, the target of which is the spatial location being attended to. During the eye movement, the visual input is assumed to be attenuated due to motion blur. After the eye movement has completed, the current foveal feature information is associated with the feature memory trace to activate a single feature class, which we identify with the actual percept. As more and more occurrences of eye movements to patches of a given color are made, the association of the peripheral and foveal features with the common color class becomes stronger. After this learning process the peripheral stimulus before the eye movement will activate the same color class as the foveal stimulus after the eye movement, thereby yielding perceptual stability.

We tested our model with a simulated learning system, in which the temporal difference Reinforcement learning technique of Sutton and Barto [13] was used to learn the association between the pre- and post-motor color features. The Sutton-Barto method can be thought of as a conditioning process, whereby a conditioned stimulus (in this case the pre-motor peripheral feature detector activity) is associated with a temporally delayed unconditioned stimulus (in this case the post-motor foveal feature detector activity). Another way to look at the temporal-difference method is that it produces a prediction, based on the occurrence of a given peripheral pre-motor feature, of the occurrence

of the associated foveal post-motor feature. During the learning process the difference between the actual value of the unconditioned stimulus and the prediction is used as the reinforcement driving the update of the associative strengths. To implement the temporal relations, this reinforcement signal is weighted by an *eligibility trace*, which is basically a short term memory of the pre-motor peripheral feature detector value.

The update procedure that we use for the associative strengths, $V_{ij}(t)$, is given by the temporal difference learning rule [13]:

$$\Delta V_{ij}(t) = \alpha[\lambda(t) + \gamma V_{ij}(t-1)X_j(t) - V_{ij}(t-1)X_j(t-1)]\bar{X}_j(t)$$

where the eligibility trace, $\bar{X}_j(t)$ is computed using a moving average:

$$\Delta \bar{X}_j(t) = \delta(X_j(t-1) - \bar{X}_j(t-1))$$

The eligibility trace is reset to zero during each attention shift (from the fovea to the peripheral saccade target). The association strengths are initialized to zero at the beginning of the learning period.

In the parlance of the conditioning literature, $\lambda(t)$ is the strength of the unconditioned stimulus. In this case, the unconditioned stimulus is the foveal feature detector response immediately after an eye movement. Before and during an eye movement, λ is taken to be zero.

The features, $X_j(t)$, used in our simulation were computed with a sharply tuned radial basis function (RBF) network [10] whose centers were fixed to 20 different color values. The centers were defined by a set of 3 sensor coordinates corresponding to the long, medium, and short wavelength photoreceptors found in the human retina. The coordinates of the 20 different centers were derived from the projection of 10 different spectral distributions, corresponding to randomly selected Munsell color patches (as measured by Parkkinen *et al.* [9]), onto the 6 spectral sensitivity curves shown in figure 1. These 6 sensitivity curves correspond to the 3 (peripheral) cone sensitivities measured by Stockman *et al.* and the 3 foveal cone sensitivities, computed by applying the wavelength dependent macular and lens absorption curves provided by Stockman *et al.* to the peripheral curves. Thus half of the RBF centers corresponded to foveally sensed colors and the other half to those same colors as viewed in the periphery. We did not model the variation in spatial density of the photoreceptors in our simulation, only the variation in spectral response.

The simulation was divided into 100 fixation cycles. Each cycle consisted of three phases: allocation of attention to the periphery, which lasts for 7 simulator

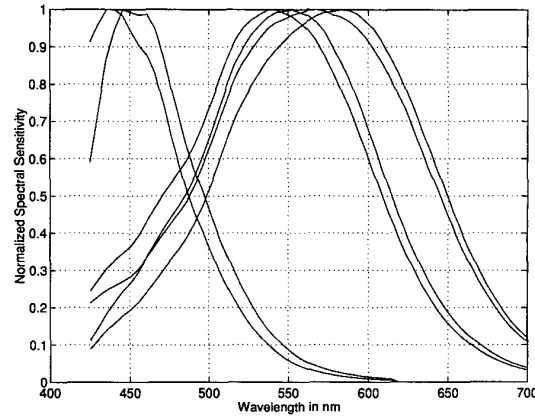


Figure 1. The normalized spectral sensitivity curves of the 3 main receptor classes (Short, Medium, and Long wavelength), in the fovea and in the periphery. The foveal curves are shifted to longer wavelengths by macular and lens absorption.

time steps; saccadic eye movement to the peripheral target, which lasts for 2 simulator time steps; allocation of attention to the fovea, which lasts for 14 simulator time steps. At the beginning of each cycle a color patch, randomly selected from the first 10 RBF centres, was placed in the periphery. Thus, the situation effectively being simulated is one in which the eye moves among a set of 100 different spatially distributed randomly colored patches.

The associative strengths learned by the network after 2300 time steps is shown in figure 2. The key aspect to note in this figure is that both features i and $i + 10$ are associated with color class i . Thus, the peripherally sensed feature $i + 10$ is associated with the foveally sensed color class, and NOT the peripherally sensed color class. Thus the color percept (being the activated color class) is constant across the saccadic eye movement.

4. Conclusions

The apparent visual stability of color percept across saccadic eye movements can be explained by positing that perception involves observing how sensory input changes in response to motor activities. The changes related to self-motion can be learned, and once learned, used to form stable percepts. The variation of sensor data in response to a motor act is therefore a *requirement* for stable perception rather than something

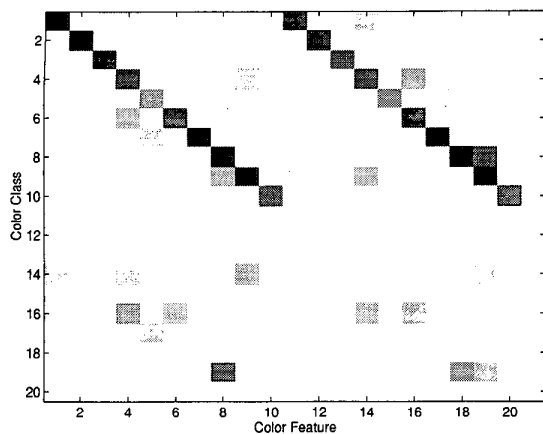


Figure 2. The associative strengths of the 20 feature detector outputs with the 20 color classes. Dark areas indicate high association levels.

which has to be compensated for in order to perceive a stable world.

In this paper we have provided a simple implementation of this sensory-motor contingency view of perceptual stability. We showed how a straightforward application of the Sutton-Barto temporal-difference reinforcement learning technique can yield color percepts that are stable across saccadic eye movements, even though the raw sensor input may change radically.

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