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High-Level Aftereffects to Global Scene Properties

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Adaptation is ubiquitous in the human visual system, allowing recalibration to the statistical regularities of its input. Previous work has shown that global scene properties such as openness and mean depth are informative dimensions of natural scene variation useful for human and machine scene categorization (Greene & Oliva, 2009b; Oliva & Torralba, 2001). A visual system that rapidly categorizes scenes using such statistical regularities should be continuously updated, and therefore is prone to adaptation along these dimensions. Using a rapid serial visual presentation paradigm, we show aftereffects to several global scene properties (magnitude 8–21%). In addition, aftereffects were preserved when the test image was presented 10 degrees away from the adapted location, suggesting that the origin of these aftereffects is not solely due to low-level adaptation. We show systematic modulation of observers' basic-level scene categorization performances after adapting to a global property, suggesting a strong representational role of global properties in rapid scene categorization.

Keywords: scene recognition, aftereffects, global property, natural images, gist

Just as a brief glance at a face can give a wealth of information about the person's age, gender, race, mood, and attractiveness, a brief glance at a scene provides the observer with equally rich and varied information (Intraub, 1981; Oliva & Schyns, 2000; Potter, 1975). This brief glance can provide knowledge about whether the scene is indoors or outdoors (Fei-Fei, Iyer, Koch, & Perona, 2007); if outdoors, whether it is natural or urban (Greene & Oliva, 2009a; Joubert, Rousselet, Fize, & Fabre-Thorpe, 2007; Rousselet, Joubert, & Fabre-Thorpe, 2005); if there is a clear path for navigation (Greene & Oliva, 2009a; Kaplan, 1992); and even a sense of the pleasantness of the environment (Kaplan, 1992).

In addition to rapid processing, behavioral and computational work has shown that certain *global scene properties* that represent the structure and function of a scene (such as openness, mean depth, and potential for navigation) are correlated with a scene's basic-level scene category (Greene & Oliva, 2009b; Oliva & Torralba, 2001). In a recent study, Greene and Oliva (2009b) observed that human observers' errors in rapid scene categorization were better predicted by the similarity between target and distractor images in a global property space than by similarity in an object space. For example, given a brief glimpse of a scene (50 ms), observers were more likely to confuse river and forest scenes, which have very similar spatial layout properties (for example, both tend to be enclosed and concealed environments with a relatively low potential for efficient navigation), than to confuse forest and field scenes, which have very different spatial layout properties (for example, fields are more open than typical forests, and have less potential for concealment but greater potential for navigation), even though they share similar objects. Computational work has shown that a system can categorize pictures of scenes, particularly outdoor environments, by using localized combinations of low-level features, such as texture elements, spatial frequency, orientation, and color, without the need to segment the objects that compose the scene (Fei-Fei & Perona, 2005; Oliva & Torralba, 2001; Torralba & Oliva, 2002, 2003; Vogel & Schiele, 2007; Walker Renninger & Malik, 2004, among others), indicating that, in principle, scene classification can be accomplished with information that is more global than objects or segmented regions. Altogether, these results suggest a global, *scene-centered* view of scene understanding in which the meaning of a scene can be understood from the rapid computation of global scene properties representing aspects of scene structure and affordance.

A scene-centered framework of recognition predicts that the visual system should be continuously updated to structural and functional regularities that are useful for recognition and action and therefore prone to adaptation along these dimensions. Just as adaptation is observed in the relevant coding dimensions for faces such as emotion, gender, and identity (Leopold, O'Toole, Vetter, & Blanz, 2001; Webster, Kaping, Mizokami, & Duhamel, 2004), we would expect that the human visual system also adapts to scene properties that are relevant for scene analysis. Broadly, *aftereffects* are measured changes in the perceptual appearance of Stimulus B after being adapted through prolonged exposure to Stimulus A. The effects of adaptation tend to bias perception away from properties of the adapting stimulus, such that Stimulus B appears less like Stimulus A after adaptation. As it is generally thought that adaptation reflects strategies used by the neural system for optimizing perceptual mechanisms (Attneave, 1954; Barlow, 1961),

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the adaptation method has been long employed in psychology to elucidate neural mechanisms of perception (see Clifford, Wenderoth, & Spehar, 2000; Clifford et al., 2007; see Wade & Verstraten, 2005, and Webster, 1996, for reviews).

Indeed, adaptation has been observed for many features coded by the visual system, from basic features such as color, motion, orientation, and spatial frequency (Wade & Verstraten, 2005) to higher level properties such as facial emotion, gender, and identity (Leopold et al., 2001; Webster et al., 2004). Adaptation also has been shown to transfer between sensory modalities (Konkle, Wang, Hayward, & Moore, 2009). Furthermore, adapting to low-level image features can modulate higher level perceptual judgments. For example, adapting to lines curved like a smile can modulate perceived face emotion (Xu, Dayan, Lipkin, & Qian, 2008), adapting to subtle relationships between dots can alter the perceived gender of point-light walkers (Troje, Sadr, Geyer, & Nakayama, 2006), adapting to textures with different skewness can change the perceived glossiness of surfaces (Motoyoshi, Nishida, Sharan, & Adelson, 2007), and adapting to textures with different orientation content can alter the perceived naturalness of real-world scenes (Kaping, Tzvetanov, & Treue, 2007). The converse is also true: Adaptation to the direction of implied motion from static photographs of movement (a racecar driving, for example) creates a measurable motion aftereffect in a random dot coherence measure (Winawer, Huk, & Boroditsky, 2008). Furthermore, adaptation to a large number of natural scenes can influence observers' contrast sensitivity functions, lowering sensitivity to low to medium spatial frequencies, as predicted by the 1/f frequency structure of natural images (Webster & Miyahara, 1997). Each of these examples illustrates how low-level features can alter high-level perception and categorization (and vice versa); however, it has not yet been shown how adaptation to complex natural inputs such as scenes can alter the perception of subsequently presented natural scenes.

The goal of this work was to determine whether global aspects of natural scene structure and affordance can produce aftereffects that alter the perception of subsequently presented natural scenes. Intuitively, experiences from our daily lives tell us that this might be the case. After spending a day spelunking, the world outside of the cave might appear much larger than it did before. Many of us have had the experience of leaving our familiar environments to go on vacation in a place that looks very different from our homes, such as leaving a spacious suburb in California to visit New York City. On returning home, the differences in spatial layout between the two places might seem exaggerated: Exposure to the urban, crowded, vertical structure of Manhattan might make the backyard seem spacious and green. If our visual system efficiently codes spatial and affordance properties of natural scenes for use in rapid scene categorization, then we should observe aftereffects to global properties, and adaptation to these properties should alter the speed and accuracy of human scene categorization abilities.

Greene and Oliva (2009b) proposed a set of global scene properties designed to reflect the natural variation in natural scene categories' spatial, surface, and affordance properties (see also Appelton, 1975; Gibson, 1979; Kaplan, 1992; Oliva & Torralba, 2001). It is important to note that human observers are sensitive to these properties in rapid scene categorization tasks (Greene & Oliva, 2009b), making them good candidate properties for aftereffects.

In Experiment 1, we tested for perceptual aftereffects from adaptation to five global properties of natural scenes (*openness*, *naturalness*, *mean depth*, *navigability*, and *temperature*; see Figure 1 for pictorial examples) using a rapid serial visual presentation (RSVP) adaptation paradigm. Experiments 2–4 explored the nature of these aftereffects using the global property, openness as the case study. In Experiment 2, we ruled out the possibility that the aftereffects observed in Experiment 1 were inherited from adapting low-level (retinotopic) visual areas. Experiments 3 and 4 tested the transfer of openness adaptation to basic-level scene categorization, finding that observers' adapted state can alter the boundary between basic-level categories (Experiment 3) and change the speed of basic-level categorization (Experiment 4), suggesting a causal role for global property computation at an early stage of scene representation. Taken together, these results indicate that certain global properties of natural scenes are selectively adaptable, producing high-level aftereffects, and that such properties may be relevant for the rapid categorization of natural scenes.

Experiment 1: Aftereffects to Global Scene Properties

The goal of the first series of experiments was to determine whether aftereffects could be obtained for a set of global scene properties in RSVP adaptation paradigm. Here, we tested five global properties (openness, mean depth, naturalness, navigability, and temperature) for aftereffects. These properties were selected to be a representative sample of the global properties tested in previous work (Greene & Oliva, 2009b), reflecting spatial, affordance, and surface global aspects of landscape environments. In these experiments, we adapted participants to the extremities (or poles) of each global property dimension. Figure 1 shows examples of the poles of each of these global property dimensions. Each global property was tested in an independent experimental session. As the method and design details for all of these experiments were the same, we present the five experiments as one.

General Method

Materials. Scene images were full color, 256 × 256 pixels in size, and were chosen from a large laboratory database of real-world photographs that had been previously ranked along the dimensions of naturalness, openness, navigability, mean depth, and temperature (Greene & Oliva, 2009b). To summarize, observers performed a hierarchical grouping task that organized groups of 100 images from lowest to greatest degree of each global property by making three binary groupings that produced eight groups of images. For example, observers organized the images from the most close up to the farthest view for the case of mean depth or from coldest to hottest places in the case of temperature. Detailed description of this ranking can be found in Greene and Oliva (2009b).

Adaptation and test images were chosen from these rankings. Adaptation images were chosen from the poles (or extremes) of the ranks, and test images were moderate along the ranks (see Figure 1 for pictorial examples). For each global scene property, three groups of 100 images were chosen. First, 200 images served as experimental adaptors, 100 from each pole of the property (for example, 100 images of natural environments and 100 urban

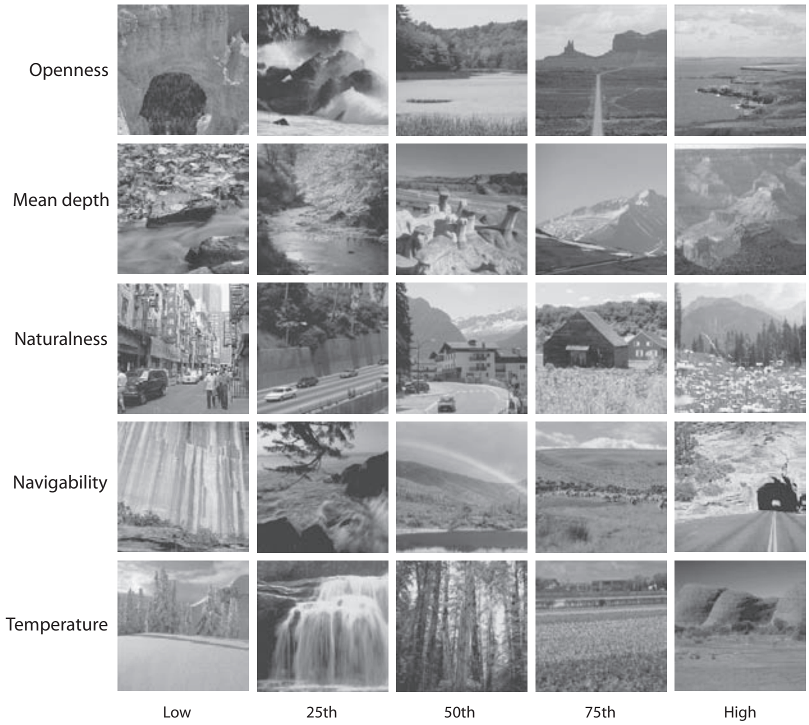

Figure 1. Example images illustrating the five global scene properties used in Experiment 1. Images on the ends were used in the adaptation phase, and images in the center were from the 25th, 50th, and 75th ranking percentiles and were used as test images.

environments in the case of naturalness). In all cases, these images were chosen to vary as much as possible in physical and semantic attributes other than the global property being tested. For example, in the case of mean depth, large-depth images would consist of panoramic images from many natural image categories (fields, oceans, farmland, mountains, canyons, etc.) with various viewpoints, object density, and lighting. The third group of 100 images served as a control adaptation condition, and represented all ranks along a given global property dimension. The test images consisted of 30 additional images for each global property that represented rank values from around the 25th, 50th, and 75th ranking percentiles (see Figure 1 for examples).

All experiments were run using MATLAB and Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Experiments were displayed on a 21-in. CRT monitor with a 100-Hz refresh rate. Images subtended approximately 7 × 7 degrees of visual angle.

Participants. A total of 46 participants from the MIT community participated in at least one experiment. Each global property was run as an independent experiment, so individual observers could participate in more than one experiment. Between 10 and 21 observers participated in each experiment. All were between 18 and 35 years old and had normal or corrected-to-normal vision. Participants provided informed consent and were paid $10/hr for their time.

Design and procedure. Each of the five global properties was tested in an independent experimental session lasting approximately 45 min. Each experiment was a within-subjects design in which participants were adapted to each pole of the global property and to the control set in three separate blocks. The order of the blocks was counterbalanced across participants.

A schema of the experimental procedure for a sample block is shown in Figure 2. Each experimental block consisted of two phases, an adaptation phase (see Figure 2A) and a testing phase (see Figure 2B). The adaptation phase lasted approximately 5 min

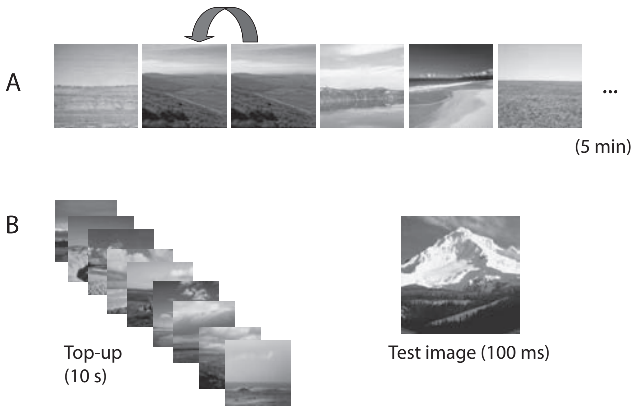

Figure 2. A schematic representation of the experimental procedure of Experiment 1. (A) A 5-min adaptation phase in which participants viewed 800 adaptor images (100 images repeated 8 times each) while performing a one-back task. (B) Each trial of the test phase consisted of a 10-s top-up adaptation in the form of a rapid serial visual presentation (RSVP) stream, followed by a test image for 100 ms.

and consisted of displaying the 100 adaptor images 8 times each in random order. Each image was shown for 100 ms, with 100 ms blank between images. To maintain focus on the image stream, participants were instructed to press the space bar when back-to-back image repeats were displayed. On average, there were seven repeats in the stream, appearing about every 80 s.

The testing phase consisted of 30 trials and immediately followed the adaptation phase. To ensure a constant level of adaptation throughout the test phase, each trial commenced with 10 s of "top-up" adaptation given in the form of an RSVP stream in which each of the 100 adaptor images was shown again for 100 ms in random order. Participants were instructed to carefully watch and attend to the 10-s image stream. Following the top-up RSVP adaptation stream, there was a 500-ms blank, followed by the test image presented for 100 ms, and then masked by a 1/f noise mask for 80 ms. Following each test image, participants were instructed to respond as quickly and accurately as possible as to which pole of the global property the test image belonged. For example, in the mean depth experiment, participants would indicate whether the test image was *large depth* or *small depth*. As test images were rated as ambiguous along the global property dimension tested, no performance feedback was given. The descriptions of the global properties as given to participants can be found in the Table 1.

Results

As aftereffects are fleeting (Rhodes, Jeffery, Clifford, & Leopold, 2007), speed was essential. At the test, trials with reaction times (RTs) greater than 2 s were discarded from the analysis (less than 5% of the data for each experiment; the mean RT over the five experiments was around 760 ms). Participants whose mean RT was more than 3 standard deviations above the group mean were not included in the analysis ($n = 6$). As each global property was tested independently, each was analyzed separately. As we did not have hypotheses about the relative magnitudes of the adaptation effects, no comparison between the properties is provided.

Figure 3 illustrates participants' responses in each experiment. For each participant in each experiment, we computed the proportion of trials in which the test image was classified as the high pole of the global property (i.e., open, natural, hot, large depth, and navigable) for each of the three groups of test images (25th, 50th, and 75th ranking percentiles). The proportion of high-pole responses following adaptation to each pole of a global property was compared against the responses following adaptation to the control stream to establish a baseline for how the test images would be classified in our paradigm. As shown in Figure 3, participants' classifications of the same test scenes differed systematically with their adaptation condition. For example, adaptation to open images made the moderately open test images appear more closed than after viewing the control stream of images. It is important to note that the same test images were perceived by the same observer as more open after adapting to closed images.

Repeated measures analysis of variance (ANOVA) was performed on the average proportion of test images classified as the high pole of the global property for each experimental session, across the three adaptation conditions (high and low global property poles plus control), for the three groups of test images (25th, 50th, and 75th ranking percentiles). As expected, there were significant main effects of test image ranking group (25th, 50th, or 75th ranking percentile) on classification, indicating that relative rankings were maintained: $F(2, 40) = 70.41$, $p < .0001$, for openness; $F(2, 18) = 99.50$, $p < .0001$, for naturalness; $F(2, 30) = 37.71$, $p < .0001$, for temperature; $F(2, 30) = 60.92$, $p < .0001$, for mean depth; and $F(2, 26) = 64.57$, $p < .0001$, for navigability. In addition, there was a significant main effect of adaptation condition for openness, $F(2, 40) = 19.51$, $p < .001$; naturalness, $F(2, 18) = 10.8$, $p < .001$; temperature, $F(2, 30) = 19.71$, $p < .001$; mean depth, $F(2, 30) = 7.95$, $p < .005$; and navigability, $F(2, 26) = 3.69$, $p < .05$. The mean magnitude of the aftereffects (the overall difference between adapting to one global property pole vs. the other, and collapsing over the three groups of test images) was 21% for temperature, 20% for naturalness, 15% for openness, 13% for mean depth, and 8% for navigability.

We next determined whether both poles of each global property showed significant adaptation. For each participant and for each adaptation condition, we collapsed over the three groups of test images, subtracting the "high-pole" responses in the experimental adaptation conditions from the "high-pole" responses in the control condition. For each global property, we contrasted these values with the null hypothesis that these numbers were zero, indicating the absence of aftereffects. Average magnitudes are shown in the right-hand column of Figure 3. For all global properties except navigability, both global property poles were significantly different from zero ($p < .05$).

Discussion

Here, we have shown that several global scene properties related to scene spatial layout and function can produce aftereffects. Experiment 1 demonstrated robust aftereffects to four global properties (naturalness, openness, temperature, and mean depth).

The property navigability showed a weak and one-directional aftereffect, as shown in Figure 3E. This is a puzzling result as this property has previously been shown to be easily detected in brief

Table 1
Descriptions of the Global Scene Property Poles

Global property	Description High pole	 Low pole
Mean depth	The scene takes up kilometers of space.	The scene takes up less than a few meters of space.
Naturalness	The scene is a natural environment.	The scene is a manmade, urban environment.
Navigability	The scene contains a very obvious path that is free of obstacles.	The scene contains many obstacles or difficult terrain.
Openness	The scene has a clear horizon line with few obstacles.	The scene is closed, with no discernible horizon line.
Temperature	The scene environment depicted is a hot place.	The scene environment depicted is a cold place.

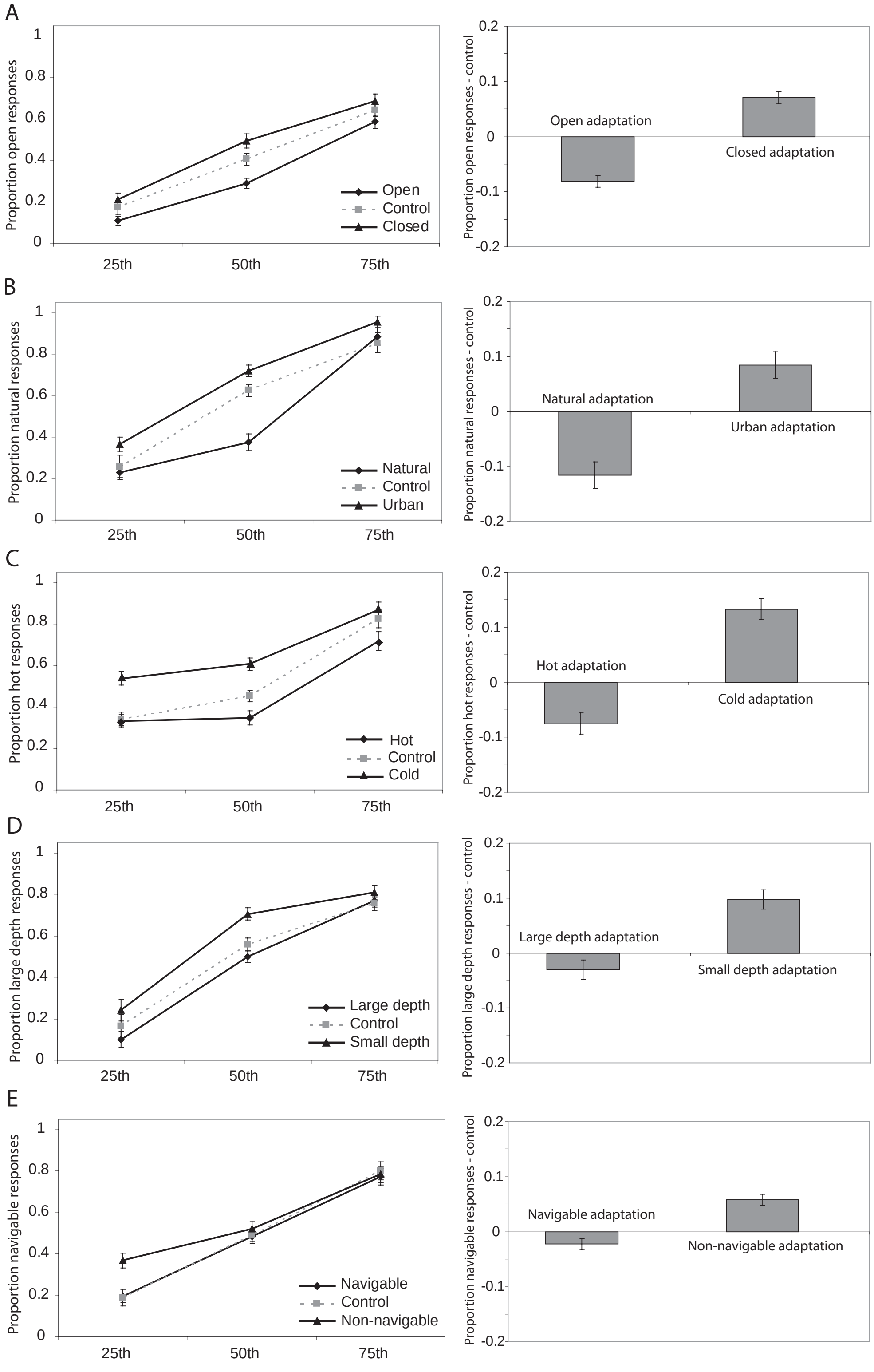

Figure 3. Results from Experiment 1. The properties are, from top to bottom, (A) openness, (B) naturalness, (C) temperature, (D) mean depth, and (E) navigability. Error bars correspond to ±1 within-subjects *SEM* (Loftus & Masson, 1994). Graphs in the left column show proportion of responses to the high pole of each global property for the three groups of test images over the three adaptation conditions. Graphs in the right column show the magnitude of the effect in each direction by showing the proportion of high-pole responses for the two global property poles subtracted from responses to the control condition.

glances of scene images (Greene & Oliva, 2009a) and used by human observers to perform rapid basic-level scene categorization (Greene & Oliva, 2009b). One possibility is that navigability might be a multimodal property, particularly for highly navigable images. A very open scene can be navigable as can a closed scene with a clear path in it. Given the very heterogeneous nature of the adaptation stream, perhaps a longer adaptation period is necessary for this property. Another possibility is that it is not navigability per se that adapts, but rather information that is correlated with nonnavigable environments. For example, very low navigability environments tend to be closed environments made up of dense textures (from elements such as thick brush or rock outcroppings), suggesting that the unilateral aftereffect could reflect adaptation to closedness or texture density (Durgin & Huk, 1997).

Although aftereffects have been reported from viewing streams of natural images (Webster & Miyahara, 1997), to our knowledge, this is the first laboratory demonstration of such aftereffects altering the perception of subsequently viewed natural images. The global scene properties tested here are known to reflect a large amount of the variability existing between natural scene categories (Appelton, 1975; Baddeley, 1997; Gibson, 1979; Greene & Oliva, 2009a, 2009b; Joubert et al., 2007; Kaplan, 1992; Rousselet et al., 2005) and are informative dimensions describing differences between basic-level scene categories (Greene & Oliva, 2009b; Oliva & Torralba, 2001).

Adaptation is generally seen as a functional mechanism used by the visual system to efficiently encode changes in the visual world (Attneave, 1954; Barlow, 1961). In this framework, the visual system can store an average (or prototype) value for a stimulus and encode individual exemplars as differences from this prototype (Leopold et al., 2001). For environmental scenes, this prototype may reflect the mode of experienced scene properties. In other words, this prototype reflects the most common values of scene spatial layout and function that one has experienced.[1] The existence of aftereffects to global properties of natural scene variability suggests that adaptation may play a role in our daily lives, continuously recalibrating our visual systems on the basis of the statistical regularities of experienced scenes.

An outstanding question is the extent to which the aftereffects observed in Experiment 1 are a result of adaptation of multiple low-level features rather than adaptation of the global properties as single, high-level entities. Indeed, the global properties of naturalness, openness, and mean depth are also well correlated with low-level image features such as combinations of localized orientations and spatial frequencies (Oliva & Torralba, 2001; Torralba & Oliva, 2002). For example, a high degree of openness is correlated with low spatial frequency horizontal orientation in the vertical center of the image, a feature that corresponds with the horizon line of the scene, whereas a low degree of openness is correlated with more uniform texture throughout the image (Oliva & Torralba, 2001). Similarly, the judgment of how hot or how cold a place is (i.e., temperature) is related to the reflectance, color, and material properties of scene surfaces, such as the difference between desert sandstone and an iced-over river; and aftereffects have been observed to texture and material properties (Durgin & Huk, 1997; Motoyoshi et al., 2007). Therefore, it is possible that the aftereffects observed in Experiment 1 could be inherited from the low-level adaptation of visual features. We addressed the nature of global property aftereffects in Experiment 2.

Experiment 2: Translation Invariance of Openness Aftereffect

As robust aftereffects have been demonstrated for low-level features (for review, see Clifford et al., 2007), we addressed the extent to which the aftereffects observed in Experiment 1 were due to adaptation of low-level features inherited from early visual areas.

A standard method for gaining insight into the processing level of aftereffects has been to test the translation invariance of the effect. As early visual areas have small receptive fields, adaptation of cells in these areas will not be invariant to a shift in location, whereas later visual areas show greater tolerance to this transformation (Gross, 1973; Ito, Tamura, Fujita, & Tanaka, 1995). Melcher (2005) examined a variety of aftereffects and found that the degree of spatial tolerance of the effects is related to the complexity of the stimulus: Contrast adaptation had no spatial transfer, but faces had considerable transfer (cf. Jiang, Blanz, & O'Toole, 2006; Leopold et al., 2001; Rhodes et al., 2005; but see Afraz & Cavanagh, 2008). In Experiment 2, we tested the spatial tolerance of global scene property aftereffects, using the global property of openness as a test case.

A new group of participants was adapted to images centered 5 degrees of visual angle to the right or left of a central fixation. Aftereffects were probed in the opposite hemifield, 5 degrees away from fixation in the opposite direction from where adaptation occurred. If the aftereffects observed in Experiment 1 were inherited from adaptation of low-level visual features from early visual areas, then we would not expect to observe an aftereffect in Experiment 2. However, if the aftereffect is invariant to the hemifield transformation, then it suggests the existence of a high-level aftereffect.

Method

Participants. Ten new observers from the MIT community participated in Experiment 2. All were between 18 and 35 years old and had normal or corrected-to-normal vision. As eye fixation was monitored with an eye tracker, only participants without eyeglasses were selected. Participants provided informed consent and were paid $10/hr for their time.

Materials. The same set of images used for testing adaptation to openness in Experiment 1 was used. Participants' right eye positions were monitored with an ETL 400 ISCAN table-mounted video-based eye-tracking system (ISCAN Inc., Burlington, MA) sampling at 240 Hz. Participants sat 75 cm from the display monitor and 65 cm from the eye-tracking camera, with their head

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[1] There is also the possibility of an exemplar-based space model as exists in the face recognition literature (Valentine, 1991). In prototype and exemplar spaces, stimuli are coded by a number of dimensions reflecting some typically nonspecified stimulus features. The primary difference between the two models is that the prototype account stores exemplars as vectors from the mean (or prototype), whereas the exemplar model codes each stimulus as a point in the space representing its values along the feature dimensions of the space. Although these two models can be experimentally distinguished by testing for adaptation along arbitrary trajectories (those that do not go through the mean; see Robbins et al., 2007), the current series of experiments is agnostic to this distinction.

centered and stabilized in a headrest. The position of the right eye was tracked and viewing conditions were binocular.

Design and procedure. The design and procedure for Experiment 2 were identical to those of Experiment 1 except that the 5-min adaptation phase and the top-up adaptation streams were presented at a location centered 5 degrees to one side of a central fixation point, and test images were centered 5 degrees on the other side. The side that was adapted was counterbalanced across participants. Images were approximately 5.3×5.3 degrees of visual angle in size, and there was no spatial overlap between adaptation and test locations. Eye position was monitored throughout the experiment, and trials in which the eyes moved more than 1 degree away from central fixation were discarded from analysis (this corresponds to two trials from one participant, none for all others).

Results

As in Experiment 1, for each participant, we computed the proportion of trials in which the participant classified test images as open for each of the three groups of test images. Also as in Experiment 1, trials with RTs greater than 2 s were discarded from analysis (3.4% of data). Repeated measure ANOVA was performed on the average proportion of images classified as open for each observer for each adaptation condition and for each of the test groups. As observed in Experiment 1, there was a significant main effect of ranking level of the test images: $F(2, 18) = 22.89$, $p < .001$. There was also a significant main effect of adaptation condition, $F(2, 18) = 10.59$, $p < .01$, indicating that the openness aftereffect survived a 10 degree spatial shift.

As in Experiment 1, we then tested whether the aftereffect was significant for both global property poles. Indeed, the open, $t(9) = 3.12$, $p < .05$, and closed, $t(9) = 3.04$, $p < .05$, poles showed significant aftereffects. The magnitude of the adaptation effect (the summed magnitude from each pole) was 14%, which was similar to the 15% magnitude observed in Experiment 1. This degree of spatial invariance is similar to the results reported in the face adaptation literature (Jiang et al., 2006; Leopold et al., 2001; Melcher, 2005; Rhodes et al., 2003).

Discussion

Here, we have shown that the openness aftereffect observed in Experiment 1 has strong position invariance and is therefore unlikely to be solely due to the cumulative adaptation across multiple low-level features from early visual areas. This result suggests that what is being adapted is a higher level representation of the degree of openness of a scene.

This result is consistent with the general finding that low-level aftereffects are specific to the adapted location, size, and orientation, whereas high-level aftereffects display some tolerance to these manipulations (Jiang et al., 2006; Leopold et al., 2001; Melcher, 2005; Rhodes et al., 2005). This is somewhat equivocal, however, as adaptation to a simple oriented line can lead to position-invariant shape aftereffects (Suzuki & Cavanagh, 1998), and there are limitations to the position tolerance of face aftereffects (Afraz & Cavanagh, 2008). It is an open question of where in the visual system this adaptation takes place. However, a few general points can be made. Although the eccentricity of our stimuli from the central fixation point is similar to the receptive field sizes reported to macaque V4 (Gattass, Sousa, & Gross, 1988), our stimuli were presented on opposite sides of the vertical meridian and only inferior temporal cortex has receptive fields that represent both hemifields (Gross, Rocha-Miranda, & Bender, 1972); however, the human homolog to this area is still an area of active research (Bell, Hadj-Bouziane, Frihauf, Tootell, & Ungerleider, 2009).

The current results show that there is substantial spatial transfer of aftereffects across space. Although we observed a similar magnitude of adaptation in this study, spatial transfer of face aftereffects typically find that the magnitude of the effect is 50–70% of the magnitude of the aftereffect when tested in the adapted location. Our current result suggests that the aftereffects observed in Experiments 1 and 2 are high level in nature and not simply inherited from adaptation of lower level features.

Experiment 3: The Use of Openness for Basic-Level Scene Categorization

Experiments 1 and 2 found that participants were more likely to classify test images as more dissimilar to the global property pole to which they were adapted. In other words, scenes that were, for instance, moderately natural would appear more or less natural given the observer's adapted state. Previous work has shown that global properties such as these might be used by human observers to perform rapid basic-level categorization (Greene & Oliva, 2009b). Such results would therefore predict that an observer's adapted state to a global property would influence subsequent basic-level categorization.

In Experiment 3, we examined the use of global property information for basic-level scene categorization by testing whether participants' adapted state to a global property pole would systematically influence a basic-level scene categorization task. We reasoned that if a pole of a global property is integral to the identity of a basic-level scene category, then adaptation to this property will result in systematic changes to basic-level scene categorization. In particular, as adaptation to a pole of a global property makes scenes appear more like the opposite pole, then the perception of the scene's category will shift toward categories that share the opposite global property pole.

Scenes, like objects, are preferentially categorized at the basic level (Tversky & Hemenway, 1983). For example, the scene on the far right of Figure 4 will most often be called a forest by human observers, rather than landscape or thick, deciduous forest in springtime. However, unlike objects, there can be graded degrees of category membership in natural scene categories, and an image of a natural environment can lie between multiple basic-level categories. For example, a landscape image composed of trees, water, and hills in the background has elements of forest, lake, and mountain scene categories. In this experiment, we capitalized on the fact that there exists a continuum of environments between a forest prototype, which is typically an enclosed environment, and a field prototype, which is typically open (see Figure 4 for examples). Therefore, if openness is important to the categorization of forests and fields, then adaptation to very open scenes should make an ambiguous image on the field–forest continuum look more like a forest, and adaptation to very closed scenes should make that image look more like a field. In Experiment 3, we used an adaptation method analogous to Experiment 1 in which test images

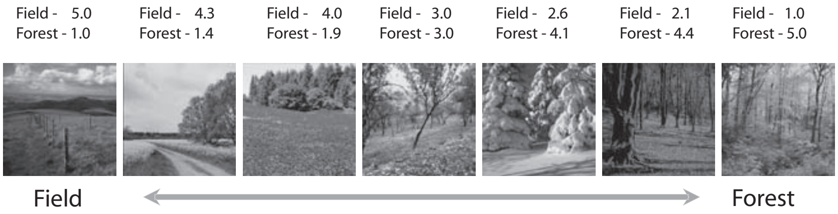

Figure 4. Examples of images ordered along the field–forest continuum, along with their prototypicality ratings for field and forest categories from Greene and Oliva (2009b). Environmental scenes, unlike most objects, can belong to more than one basic-level category. Experiment 3 tested images from the middle of the row, and Experiment 4 tested images from the ends.

were exemplars ranked as lying between forest and field prototypes. As we measured shifts in the open–closed dimension in response to adaptation in Experiments 1 and 2, in Experiment 3, we measured shifts in the forest–field dimension (see Figure 4).

Method

Participants. Twelve participants (9 new and 3 from Experiment 1 or 2) from the MIT community participated in this experiment. All were between 18 and 35 years old and had normal or corrected-to-normal vision. Participants provided informed consent and were paid $10/hr for their time.

Materials. In this experiment, it is important that observers adapt only to the openness of environments and not to the categories of forest and field. Therefore, we removed forest and field images from the adaptation streams, replacing them with images from other basic-level categories such as ocean, canyon, desert, beach, etc.

Test images were chosen from a database of natural images previously ranked on their prototypicality in regards to various basic-level categories (Greene & Oliva, 2009b, Experiment 3). In this previous study, 10 observers ranked 500 images of natural landscapes in terms of how typical each image was for each of several basic-level scene category labels using a scale from 1 (*atypical*) to 5 (*highly prototypical*). For the current experiment, the test images consisted of 30 natural landscape images that had been ranked as partially prototypical for the forest and field categories. Analogous to Experiments 1 and 2, three groups of test images were chosen: 10 images that were ranked as more field than forest, 10 that were equally prototypical of field and forest, and 10 that were more forest than field. Figure 4 shows example images along the ranked continuum between forest and field.

Procedure. As in Experiments 1 and 2, each participant completed three experimental blocks that contained two phases, an adaptation phase and a test phase. The adaptation phase of each block was identical to Experiment 1. Following the adaptation phase, participants completed a test phase that was identical to that of Experiment 1 except that the instructions were to classify test images as forests or fields as quickly and accurately as possible. As in Experiment 1, no performance feedback was given.

Results

Trials with RTs greater than 2 s were discarded from analysis (4.1% of data), and one participant with a mean RT of 3,843 ms was not included in the analysis. As also found in Experiments 1 and 2, we observed a significant main effect of test image ranking level, $F(2, 20) = 45.28$, $p < .0001$. As shown in Figure 5A, adaptation to openness modulated participants' basic-level classifications of natural scene images. After adapting to open images, participants were more likely to classify ambiguous test images as forests rather than fields. Conversely, after adapting to closed scenes, ambiguous test images were more likely to be categorized as fields, $F(2, 20) = 17.87$, $p < .001$. The overall magnitude of the effect was 11% (see Figure 5B). Whereas adapting to open scenes strongly modulated test image categorization as forest or field, $t(10) = 4.88$, $p < .001$, adaptation to closed images had only a marginal effect, $t(10) = 2.21$, $p \sim .08$.

Discussion

Here, we observed that adaptation to the openness of natural environments can systematically shift the perception of a scene's basic-level category. For example, after adapting to very open environments, scenes such as ones in the middle of Figure 4 will look more like forests. However, these same images will look more like fields after adapting to closed environments. This result suggests that human observers use the relative openness of an environment when rapidly categorizing a scene as a forest or field (see also Greene & Oliva, 2009b).

The strength of the adaptation paradigm is that it allows one to probe visual properties that are different from but that may depend on the adapted property. For example, Fang, Ijichi, and He (2007) tested whether the coding of face viewpoint is independent of face identity and gender using a transfer paradigm in which participants were adapted to an individual face at a particular viewpoint, and then asked to identify the viewpoint direction of a test face that could be either the same or different individual or same or different gender as the adaptor face. This study found evidence of joint coding as adaptation did not completely transfer over gender or identity. Similarly, Fox and Barton (2007) examined the degree to which the face expression aftereffect transfers to images of the same person, a different person of the same gender, or a different person of the opposite gender, finding a large magnitude cost in each transfer.

It is important to note that, for example, although openness is a property of a typical field, openness and "fieldness" are not equivalent concepts. Other basic-level categories such as beaches, lakes, and canyons can also share the property of openness, and any given basic-level category is defined by a collection of properties,

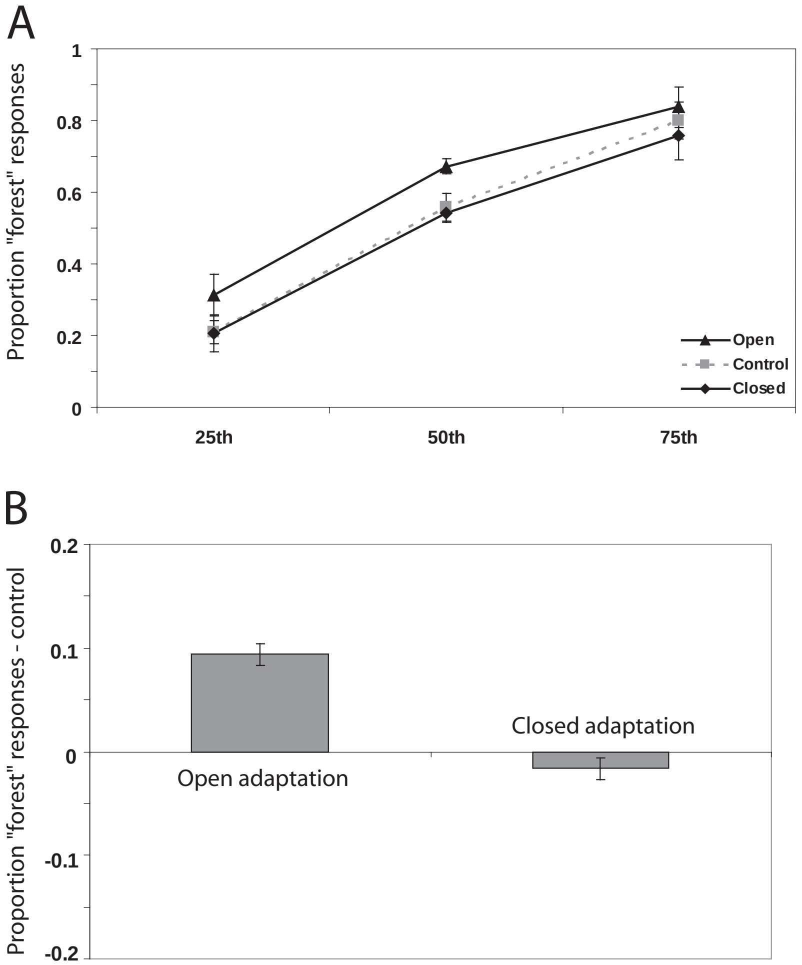

Figure 5. Results of basic-level categorization (field or forest) after adaptation to open or closed images. (A) Results of Experiment 3: Aftereffects to ambiguous images along the forest–field continuum: Adapting to open scenes makes ambiguous images appear more like forests. (B) Results of Experiment 3: The magnitude of the aftereffect in each direction is shown by showing the proportion of "open" responses for adaptation to the two global property poles subtracted from responses to the control condition. Error bars correspond to ±1 within-subjects *SEM* (Loftus & Masson, 1994).

none sufficient to categorize on its own. Furthermore, fields and other basic-level categories vary in their degree of openness (see Greene & Oliva, 2009b, Figure A1; Oliva & Torralba, 2001). Therefore, although openness may not be formally orthogonal to the basic-level categories of forest and field, the transfer of adaptation observed in Experiment 3 is not a reframing of the results from Experiment 1, but rather reflects a transfer to a different visual categorization task.

Experiment 3 suggests that the perception of openness influences the rapid categorization of scenes as forests or fields, implying that basic-level categorizations might be mediated through the computation of structural properties such as openness. If this were the case, then we would expect that the categorization of prototypical forests and fields also to be modulated by the observers' adapted state to openness. We directly tested this hypothesis in Experiment 4.

Experiment 4: Adaptation to Openness Modulates Rapid Scene Categorization

Experiment 3 demonstrated that adaptation to a global property can change the classification of basic-level categories: Exposure to closed or open scenes can change whether an ambiguous image would be classified as a member of the forest or field category. This result suggests that openness may play a role in the rapid categorization of natural images as forests or fields. If the perception of global scene properties such as openness is necessary for rapid and accurate basic-level categorization, then an observer's adapted state should change the speed and accuracy of prototypical scene categorization. This was explored in Experiment 4. As in Experiment 3, participants in Experiment 4 were first adapted to streams of open and closed scenes. Following adaptation, they performed a basic-level categorization task on pictures of prototypical forests and fields. If the perception of openness is part of the scene representation allowing rapid basic-level categorization, then we predicted the following cross-over interaction: Participants should be slower and less accurate in categorizing fields after adapting to open images and slower and less accurate in categorizing forests after adapting to closed images.

Method

Participants. Ten participants (six new and four who had participated in Experiment 1, 2, or 3) participated in this experiment. All were between 18 and 35 years old and had normal or corrected-to-normal vision. Participants provided informed consent and were paid $10/hr for their time.

Materials. The adaptation images in this experiment were the same images used in Experiment 3. The images used at test were 30 prototypical forests and 30 prototypical fields. The prototypicality of these scenes was determined from a previous ranking study (described in Experiment 3, with additional details in Greene & Oliva, 2009b). Images were determined to be prototypical if their mean ranking as forest or field was greater than 4 on a 5-point scale and were not ranked as prototypical for any other scene category.

Procedure. Participants completed a two-block experiment in which they were adapted to open and closed images in different blocks. Half of the participants adapted to open first, the other half to closed first. As we were only looking for an interaction in the experimental adaptation conditions, the control block of images was not used in this experiment. As in Experiments 1–3, each experimental block contained an adaptation phase and a test phase. The adaptation phase was identical to Experiment 3. In the test phase, participants performed a basic-level categorization task on prototypical forest and field images following the top-up RSVP adaptation before each trial. Participants were instructed to respond as quickly and accurately as possible as to whether the test image was a forest or a field. Because test images were prototypical exemplars of a scene category, visual response feedback was given (the word “Error” appeared on the screen for 300 ms following an incorrect categorization).

Results

For this experiment, we analyzed both RT and accuracy. RTs greater than 2 s were discarded from analysis (<1% of data). Data from one participant with mean RT of 2,923 ms (group mean RT was 660 ms) were not included in the analysis. For the remaining participants, accuracy in this experiment was very high, approaching ceiling performance (accuracy mean of 95% correct, median of 96% correct). Therefore, the predicted interaction between scene category and adaptation condition was not observed, $F(1, 8) < 1$, for the accuracy data. However, for RTs, we did observe a significant interaction between basic-level category and adaptation condition, $F(1, 8) = 40.32$, $p < .001$. As shown in Figure 6, observers were on average slower to categorize fields ($M = 696$ ms) than forests ($M = 584$ ms) after adapting to open images, $t(8) = 4.37$, $p < .01$. Adaptation to closed images did not have a significant effect on RT ($M = 679$ ms for fields, $M = 681$ ms for forests).

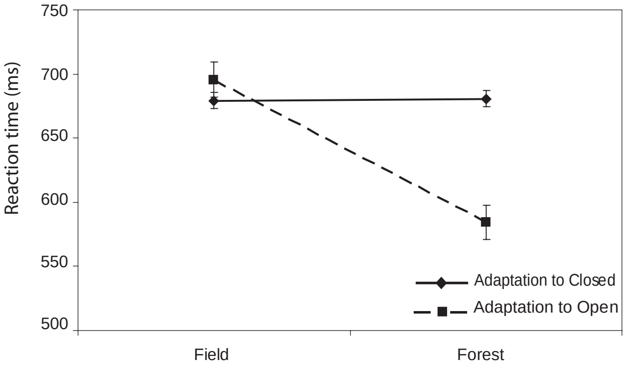

Figure 6. Results of Experiment 4: Reaction time to categorizing prototypical images of fields and forests, after adaptation to open and closed scenes. Error bars correspond to ±1 within-subjects *SEM* (Loftus & Masson, 1994).

Discussion

Experiment 3 demonstrated that adapting to open or closed scenes could push the perception of novel ambiguous scenes toward being perceived as more field- or forest-like, and Experiment 4 went one step further, showing that the speed of categorization of prototypical forests and fields could be altered by the participants’ adapted state to openness. For Experiments 3 and 4, there was an asymmetric pattern of adaptation: The effect was particularly strong for adaptation to open but not for closed images. One possibility is that open images are more homogeneous than closed scenes. Closed scenes can vary in their mean depth, navigability, roughness, and other global properties. Open scenes, on the other hand, are characterized by a prominent horizon line. This unique spatial layout also means that open scenes have a rather large mean depth and are often navigable. It is an interesting issue for future work to determine whether this homogeneity among open scenes means that openness might be more of a categorical rather than dimensional entity.

With the results of Experiment 3, the present results suggest a representational role for global properties in the rapid computation of a scene’s basic-level category. As adaptation targets neural populations coding openness, the observed decrements in the speed of scene categorization can be taken as additional evidence of the openness property’s role in representing these basic-level categories.

It is important to note that Experiments 3 and 4 are the first behavioral evidence of a transfer of high-level adaptation to a basic-level categorization task, providing critical insight into neural mechanisms that depend on the adapted property. In the case of natural image understanding, this provides a method for causally determining global scene properties that make up the representation of basic-level scene categories. Future work will involve elucidating which global scene properties participate in the representation of other basic-level scene categories (Greene & Oliva, 2009b).

General Discussion

Here, we have demonstrated aftereffects to several global scene properties (Experiment 1). These aftereffects are not due to adaptation inherited from early visual areas (Experiment 2), and do not solely reflect a shift in the observers’ decision criteria regarding the global scene properties (Experiment 3). Furthermore, we have demonstrated the perceptual consequences of global property adaptation to rapid scene categorization (Experiments 3 and 4), furthering the view that rapid scene analysis may be driven by the perception of such global properties (see also Greene & Oliva, 2009b).

Many of us have had the experience of traveling from our homes to a destination with very different visual features. For example, one might travel from a cold Boston winter to a sunny Florida beach. On returning from the trip, we might feel that our home is more gray and cold than remembered. Similarly, a city in the western United States might seem very open after visiting the dense and enclosed cities of the East Coast. Such experiences demonstrate how our visual system adjusts to the input statistics of our current environment. In this laboratory demonstration, we have shown that this process can be rapid, with measurable effects occurring after only 5 min of exposure to particular scene types. However, adaptation occurs at many time scales (Wainwright, 1999), and can function either to adjust minute changes in scene statistics or to adjust to chronic visual conditions. As the magnitude of aftereffects tends to increase logarithmically with increased exposure (Krauskopf, 1954; Leopold, Rhodes, Muller, & Jeffery, 2005; Wolfe, 1984), the aftereffects in our experiments were fleeting, but the aftereffects after longer exposure to a property might be less so.

Although a variety of high-level aftereffects have been reported for faces (Leopold et al., 2001; Rhodes et al., 2005; Webster et al., 2004), relatively little work has been done investigating perceptual aftereffects to real-world scenes. One exception has been from Kaping and colleagues (2007). In that study, participants were adapted to texture patterns that had orientation distributions that were similar to either natural or urban images. Following adaptation, participants categorized moderately urban images as either natural or urban. They found that when the orientation statistics of the adapting textures matched natural scenes, the test images were more consistently classified as urban, and the reverse also was true for adapting images matching urban scene statistics. Our results are completely congruent with this study as we also found robust adaptation to naturalness using our paradigm. However, whereas the Kaping et al. (2007) study demonstrates that adapting to a single image statistic alters the perception of scenes, our study demonstrates that considerable exposure to scenes with a specific set of global property regularities can alter the perception of subsequent scene images.

The set of global properties used here was designed to describe major dimensions of natural scene variation, not to be an independent basis for describing scenes. There is some significant covariation between properties (Greene & Oliva, 2009b). In our experiments, attempts were made to test the properties as independently as possible. Our adaptation paradigm used a large number of real-world scenes that were selected to vary as much as possible in all spatial, semantic, and low-level properties as possible while maintaining a consistent rank along the particular global property dimension.

Experiments 3 and 4 demonstrated that prolonged exposure to scenes that were highly open or closed could alter subsequent categorization of scenes at the basic level, suggesting a role for openness in the rapid categorization of forest and field images. However, there is another possible interpretation of this result. Although openness and “fieldness” are not equivalent concepts (there can be fields of varying openness and other scene categories that are also open), it is possible that global properties and basic-level categories are both multidimensional constructs with shared dimensions. According to this view, openness itself could comprise several subdimensions, rather than being a single entity, and the transfer of adaptation observed in Experiments 3 and 4 could be explained by the number of subdimensions shared between openness and the scene categories. Certainly, there are other scene properties that are covariant with both basic-level categories and global properties. For example, the properties of roughness and mean depth are also correlated with forests and fields (Oliva & Torralba, 2001), and open scenes, such as beaches and lakes, have a lower average texture density than closed scenes, such as rivers and mountains. The question of whether the adaptation we observed reflects the adaptation of multiple covariant properties could be determined in future work by running the transfer experiment in reverse: by adapting participants to a category, such as forest, and then testing for a change in the perception of a test scene’s openness. If the transfer of adaptation observed in Experiments 3 and 4 is due to shared dimensions between global properties and scene categories, then we should observe adaptation transfer. It is important to note that neither interpretation of global property construction undermines the conclusions of Experiments 3 and 4: Adaptation to openness (whether a single or multidimensional construct) alters subsequent basic-level scene categorization.

A remaining question surrounds the type of neural coding that subtends global property scene aftereffects. Two basic possibilities exist: an opponent model in which global properties are coded by two neural populations coding the extremes of the dimension, or a multichannel model in which different neural populations code for different but overlapping levels of the dimension. Although both models would predict the current data, future experiments could be designed to distinguish them. Specifically, an opponent model would predict that adaptation magnitude would be greater for test stimuli that are very different from the adaptor, and the multichannel model would predict that the greatest adaptation would occur to test stimuli more similar to the adaptors (see Robbins, McKone, & Edwards, 2007, for details on the logic).

In the domain of face processing, the concept of a “face space” has been in the literature for some time (Valentine, 1991). This framework has been particularly influential because rather than encoding the local features of a face, such as eyes, nose, and mouth, it represents global patterns of individual variation. This framework has allowed work to be done on high-level adaptation for faces by providing a continuous, high-dimensional space. A global scene property framework provides much of the same function: It describes large patterns of global variation over natural environmental categories in a continuous way, without the need to represent the individual objects that a scene contains. As Experiments 3 and 4 also demonstrated, adaptation provides a method for testing the utility of these candidate properties for scene tasks, such as basic-level category recognition.

References

Afraz, S., & Cavanagh, P. (2008). Retinotopy of the face aftereffect. *Vision Research, 48,* 42–54.

Appelton, J. (1975). *The experience of landscape.* London: Wiley.

Attneave, F. (1954). Some informational aspects of visual perception. *Psychological Review, 61,* 183–193.

Baddeley, R. (1997). The correlational structure of natural images and the calibration of spatial representations. *Cognitive Science, 21,* 351–371.

Barlow, H. B. (1961). Possible principles underlying the transformation of sensory messages. In W. A. Rosenblith (Ed.), *Sensory communication* (pp. 217–234). Cambridge, MA: MIT Press.

Bell, A. H., Hadj-Bouziane, F., Frihauf, J. B., Tootell, R. B. H., & Ungerleider, L. G. (2009). Object representations in the temporal cortex of monkeys and humans as revealed by functional magnetic resonance imaging. *Journal of Neurophysiology, 101,* 688–700.

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10,* 443–446.

Clifford, C. W. G., Webster, M., Stanley, G., Stocker, A., Kohn, A., Sharpee, T., & Schwartz, O. (2007). Visual adaptation: Neural, psychological and computational aspects. *Vision Research, 47,* 3125–3131.

Clifford, C. W., Wenderoth, P., & Spehar, B. (2000). A functional angle on some after-effects in cortical vision. *Proceedings of the Royal Society B: Biological Sciences, 267,* 1705–1710.

Durgin, F. H., & Huk, A. C. (1997). Texture density aftereffects in the perception of artifical and natural textures. *Vision Research, 37,* 3273–3282.

Fang, F., Ijichi, K., & He, S. (2007). Transfer of the face viewpoint aftereffect from adaptation to different and inverted faces. *Journal of Vision, 7*(13), 1–9.

Fei-Fei, L., Iyer, A., Koch, C., & Perona, P. (2007). What do we perceive in a glance of a real-world scene? *Journal of Vision, 7*(1), 1–29.

Fei-Fei, L., & Perona, P. (2005). A Bayesian hierarchical model for learning natural scene categories. *IEEE Proceedings in Computer Vision and Pattern Recognition, 2,* 524–531.

Fox, C. J., & Barton, J. J. (2007). What is adapted in face adaptation? The neural representations of expression in the human visual system. *Brain Research, 1127,* 80–89.

Gattass, R., Sousa, A., & Gross, C. (1988). Visuotopic organization and extent of V3 and V4 of the macaque. *Journal of Neuroscience, 8,* 1831–1845.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton-Mifflin.

Greene, M. R., & Oliva, A. (2009a). The briefest of glances: The time course of natural scene understanding. *Psychological Science, 20,* 464–472.

Greene, M. R., & Oliva, A. (2009b). Recognition of natural scenes from global properties: Seeing the forest without representing the trees. *Cognitive Psychology, 58,* 137–176.

Gross, C. G. (1973). Visual functions of inferotemporal cortex. In: R. Jung (Ed.), *Handbook of Sensory Physiology,* Vol. VII, Part 3B. Berlin: Springer-Verlag, 451–482.

Gross, C., Rocha-Miranda, C., & Bender, D. (1972). Visual properties of neurons in inferotemporal cortex of the macaque. *Journal of Neurophysiology, 35,* 96–111.

Intraub, H. (1981). Rapid conceptual identification of sequentially presented pictures. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 604–610.

Ito, M., Tamura, H., Fujita, I., & Tanaka, K. (1995). Size and position invariance of neuronal responses in monkey inferotemporal cortex. *Journal of Neurophysiology, 73,* 218–226.

Jiang, F., Blanz, V., & O'Toole, A. (2006). Probing the visual representation of faces with adaptation: A view from the other side of the mean. *Psychological Science, 17,* 493–500.

Joubert, O., Rousselet, G., Fize, D., & Fabre-Thorpe, M. (2007). Processing scene context: Fast categorization and object interference. *Vision Research, 47,* 3286–3297.

Kaping, D., Tzvetanov, T., & Treue, S. (2007). Adaptation to statistical properties of visual scenes biases rapid categorization. *Visual Cognition, 15,* 12–19.

Kaplan, S. (1992). Environmental preference in a knowledge-seeking, knowledge-using organism. In J. H. Barkow, L. Cosmides, & J. Tooby (Eds.), *The adaptive mind* (pp. 535–552). New York: Oxford University Press.

Konkle, T., Wang, Q., Hayward, V., & Moore, C. I. (2009). Motion aftereffects transfer between touch and vision. *Current Biology, 19,* 1–6.

Krauskopf, J. (1954). The magnitude of figural after-effects as a function of the duration of the test period. *American Journal of Psychology, 67,* 684–690.

Leopold, D. A., Rhodes, G., Müller, K., & Jeffery, L. (2005). The dynamics of visual adaptation to faces. *Proceedings. Biological Sciences/The Royal Society, 272,* 897–904. doi: 10.1098/rspb.2004.3022.

Leopold, D., O'Toole, A., Vetter, T., & Blanz, V. (2001). Prototype-referenced shape encoding revealed by high-level aftereffects. *Nature Neuroscience, 4,* 89–94.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review, 1,* 476–490.

Melcher, D. (2005). Spatiotopic transfer of visual-form adaptation across saccadic eye movements. *Current Biology, 15,* 1745–1748.

Motoyoshi, I., Nishida, S., Sharan, L., & Adelson, E. (2007, May 10). Image statistics and the perception of surface qualities. *Nature, 447,* 206–209.

Oliva, A., & Schyns, P. (2000). Diagnostic colors mediate scene recognition. *Cognitive Psychology, 41,* 176–210.

Oliva, A., & Torralba, A. (2001). Modeling the shape of the scene: A holistic representation of the spatial envelope. *International Journal of Computer Vision, 42,* 145–175.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10,* 437–442.

Potter, M. C. (1975, March 14). Meaning in visual search. *Science, 187,* 965–966.

Rhodes, G., Jeffery, L., Watson, T., Clifford, C. W., & Nakayama, K. (2003). Fitting the mind to the world: Face adaptation and attractiveness aftereffects. *Psychological Science, 14,* 558–566.

Rhodes, G., Jeffery, L., Clifford, C. W. G., & Leopold, D. A. (2007). The timecourse of higher-level Face aftereffects. *Vision Research, 47,* 2291–2296.

Rhodes, G., Robbins, R., Jaquet, E., McKone, E., Jeffery, L., & Clifford, C. W. G. (2005). Adaptation and face perception: How aftereffects implicate norm-based coding of faces. In C. W. G. Clifford & G. Rhodes (Eds.), *Fitting the mind to the world: Adaptation and after-effects in high-level vision* (pp. 213–240). Oxford, England: Oxford University Press.

Robbins, R., McKone, E., & Edwards, M. (2007). Aftereffects for face attributes with different natural variability: Adapter position effects and neural models. *Journal of Experimental Psychology. Human Perception and Performance, 33,* 570–592.

Rousselet, G. A., Joubert, O. R., & Fabre-Thorpe, M. (2005). How long to get to the "gist" of real-world natural scenes? *Visual Cognition, 12,* 852–877.

Suzuki, S., & Cavanagh, P. (1998). A shape-contrast effect for briefly presented stimuli. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1315–1341.

Torralba, A., & Oliva, A. (2002). Depth estimation from image structure. *IEEE Pattern Analysis and Machine Intelligence, 24,* 1226–1238.

Torralba, A., & Oliva, A. (2003). Statistics of natural images categories. *Network: Computation in Neural Systems, 14,* 391–412.

Troje, N. F., Sadr, J., Geyer, H., & Nakayama, K. (2006). Adaptation aftereffects in the perception of gender from biological motion. *Journal of Vision, 6,* 850–857.

Tversky, B., & Hemenway, K. (1983). Categories of environmental scenes. *Cognitive Psychology, 15,* 121–149.

Valentine, T. (1991). A unified account of the effects of distinctiveness, inversion, and race in face recognition. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 43*(A), 161–204.

Vogel, J., & Schiele, B. (2007). Semantic scene modeling and retrieval for content-based image retrieval. *International Journal of Computer Vision, 72,* 133–157.

Wade, N., & Verstraten, F. (2005). Accommodating the past: A selective history of adaptation. In C. W. G. Clifford & G. Rhodes (Eds.), *Fitting the mind to the world: Adaptation and after-effects in high-level vision* (pp. 83–102) Oxford, England: Oxford University Press.

Wainwright, M. (1999). Visual adaptation as optimal information transmission. *Vision Research, 39,* 3960–3974.

Walker Renninger, L., & Malik, J. (2004). When is scene identification just texture recognition? *Vision Research, 44,* 2301–2311.

Webster, M. A. (1996). Human colour perception and its adaptation. *Network: Computation in Neural Systems, 7,* 587–634.

Webster, M., Kaping, D., Mizokami, Y., & Duhamel, P. (2004, April 1). Adaptation to natural face categories. *Nature, 428,* 557–561.

Webster, M. A., & Miyahara, E. (1997). Contrast adaptation and the spatial structure of natural images. *Journal of the Optical Society of America: Optics, Image Science, and Vision, 14*(A), 2355–2366.

Winawer, J., Huk, A., & Boroditsky, L. (2008). A motion aftereffect from viewing still photographs depicting motion. *Psychological Science, 19,* 276–283.

Wolfe, J. M. (1984). Short test flashes produce large tilt aftereffects. *Vision Research, 24,* 1959–1964.

Xu, H., Dayan, P., Lipkin, R. M., & Qian, N. (2008). Adaptation across the cortical hierarchy: Low-level curve adaptation affects high-level facial-expression judgments. *Journal of Neuroscience, 28,* 3374–3383.

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