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Tilt aftereffect due to adaptation to natural stimuli

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ABSTRACT

The human visual system continuously adjusts to the current environment. To investigate these adjustments, biases in observers' perceptions owing to changes in the visual environment are measured (visual aftereffects). Typically, the stimuli used are synthetic and are composed of oriented patterns such as lines or gratings. These patterns are known to activate individual neurons in the visual cortex, but cover only a small subset of actual visual stimulations. To overcome this drawback, recent research has focused on synthetic patterns that mimic several aspects of natural stimulation. However, the aftereffects of natural stimulation per-se remain largely unexplored. Here, we interleaved presentations of unmodified natural image adaptors, selected according to criteria favoring content at a particular orientation, with presentations of targets that test a perceived orientation. This allowed us to measure the change in the perceived orientation, namely the tilt aftereffect (TAE), which resulted from repeated image presentations. Results show a close to standard TAE with adaptor durations around 500 ms, which is reduced with longer presentations. Importantly, our method can be generalized to investigate other aftereffects by selecting images differently.

1. Introduction

Visual adaptation can be defined as the adjustment of visual processing that occurs in response to changes in visual input (Clifford et al., 2007). Typically, research about visual adaptation is performed with oriented stimuli. This is motivated by the selectivity of visual neurons (Hubel & Wiesel, 1968), and by early psychophysical results (Blakemore & Campbell, 1969; Gibson & Radner, 1937). Adaptation to such stimuli leads to a change in the response properties of early visual neurons, as measured by electrophysiology (Kohn, 2007), and to visual aftereffects that are measured psychophysically (Webster, 2011). Such studies are typically performed using synthetic patterns. For example, research about the tilt aftereffect (TAE), which is the change in the perceived orientation for stimuli near the adaptor orientation, is typically performed using synthetic lines (Gibson & Radner, 1937), gratings (Campbell & Maffei, 1971; Mitchell & Muir, 1976), or Gabor patches (Knapen, Rolfs, Wexler, & Cavanagh, 2010). However, natural vision is more complex, and the visual system operates differently for synthetic and natural input (Alam, Vilankar, Field, & Chandler, 2014; Carandini et al., 2005; Olshausen & Field, 2005). Even for synthetic patterns with natural Fourier power-spectra (Geisler, 2008; Van der Schaaf & van Hateren, 1996), obtained by randomizing the phase of the Fourier transform of natural movies or images, this holds (Froudarakis et al., 2014; Goddard, Clifford, & Solomon, 2008).

Therefore, several studies have investigated adaptation with natural stimuli, for example, the change in contrast sensitivity resulting from exposure to natural movies or images (Bex, Solomon, & Dakin, 2009; Webster & Miyahara, 1997). In such experiments, the statistics of the stimuli are approximately the statistics in natural vision. It is therefore interesting how the visual system adapts to different statistics, for example different second-order statistics. Indeed, some studies investigated this by exposing observers to distorted natural stimuli (Bao & Engel, 2012; Haak, Fast, Bao, Lee, & Engel, 2014; Zhang, Bao, Kwon, He, & Engel, 2009), but no study has investigated this with natural stimuli that were not modified.

Here, we interleaved presentations of unmodified natural images with presentations of synthetic targets that test a perceived orientation. Images were either random (unbiased), or selected according to criteria favoring content at a particular orientation (biased). We show that exposure to biased images changes the perceived orientation, compared with a reference perceived orientation obtained while being exposure to unbiased images. The obtained TAE is compared with TAE resulting from synthetic noise images having similar oriented frequency content.

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2. Materials and methods

2.1. Observers

Fourteen observers (aged 20–30 years, 5 male, 9 female) with normal or corrected-to-normal vision participated. All were naïve to the purpose of the experiment, were paid for their participation, and provided informed consent in accordance with the Declaration of Helsinki.

2.2. Apparatus

The stimuli were presented on a linearized Philips 201B4 21" CRT monitor (resolution: 1280 × 1024 pixels; refresh rate: 100 Hz), which was controlled by dedicated software. Observers were seated 100 cm from the display (occupying 23° × 18.5° of visual field) in an otherwise dark environment. The mean luminance of the display was 57.8 cd/m^2.

2.3. Stimuli and tasks

We used adaptors to affect the perceived orientation (Fig. 1A), and targets to test the perceived orientation (Fig. 1B).

2.3.1. Adaptor stimuli

Three types of adaptor stimuli were used: oriented noise patterns, biased images, and unbiased images (Fig. 1C).

Noise adaptors were random $1/f^{\alpha}$ ($\alpha = 2.5$) noise patterns (Geisler, 2008; Van der Schaaf & van Hateren, 1996) filtered in order to depict the orientation content at a particular orientation (‘*noise*’, Fig. 1C). A value of $\alpha = 2.5$ was obtained by fitting $1/f^{\alpha}$ to the Fourier spectrum of the biased images (described below). The filter for oriented content was the ‘oriented band-pass filter’ used to select the biased images (as described below, but with a Butterworth filter of order 4 instead of 2). This procedure was used to generate a pool of 100 oriented noise images that were then scaled to have a fixed RMS contrast of 23%. These images were presented in a circular window subtending 4.5° of the visual angle, whose surrounding edge was averaged smoothly with the background (linearly over 0.28°).

Image adaptors were unmodified natural images that were either selected to maximize the orientation content at a particular orientation (‘*biased*’), or selected randomly (‘*unbiased*’) (Fig. 1C). Images had the same mean luminance as the background, had a mean RMS contrast of 23%, and were presented in a circular window subtending 4.5° of the visual angle, whose surrounding edge was averaged smoothly with the background (linearly over 0.28°).

Table 1
Session types.

Session	Adaptor trials				Test trials
	Stimuli	Presentation duration	Dummy task	Count	Count
noise	Oriented noise	Predefined varying	Random button	45	135
biased	Biased images	Until response	Image categorization	45	135
unbiased	Unbiased images	Until response	Image categorization	45	135

Test trials were identical across conditions. For noise, the dummy task was to press either the left or the right mouse button, randomized across days.

Biased images were obtained by the following method. First, images labeled as plants, fungi, or animals in the public ImageNet database (Deng et al., 2009) were downloaded ($N = 60{,}000$) and were converted to grayscale. Then, from each image, the sub-images of size 256 × 256 pixels were extracted (displaced by 20 pixels vertically or horizontally in the original image), resulting in ~10,000,000 sub-images. Each sub-image was padded with 0’s on the sides to a size of 511 × 511 pixels, and its two-dimensional Fourier transform was calculated (using Matlab© function “*fft2*”). The power spectrum of this transform was then used to calculate the response of two filters: a band-pass filter, and an oriented band-pass filter. The band-pass filter was a second-order Butterworth spatial frequency filter with half-responses at 1.5 and 7.5 cycles/deg. The oriented filter was a Gaussian filter with a SD of 15° and a maximal response at 115° (i.e. the maximal response for edges oriented 25° clockwise to vertical). The response of the oriented filter was then divided by the response of the not oriented filter, and the 412 sub-images with the highest ratio were selected (all from different images). Of those, 285 were manually pruned, to remove sub-images depicting content that is unidentified, blurred, or artificial (the large number of sub-images with undesired content is an artifact of the biased selection; some images depicting a strong secondary orientation in content were also discarded). The final 129 sub-images were used in the experiment (Fig. A.1).

Unbiased images were obtained by randomly selecting 513 of the 60,000 images described above, and cropping their 256 × 256 pixel center (Fig. A.2).

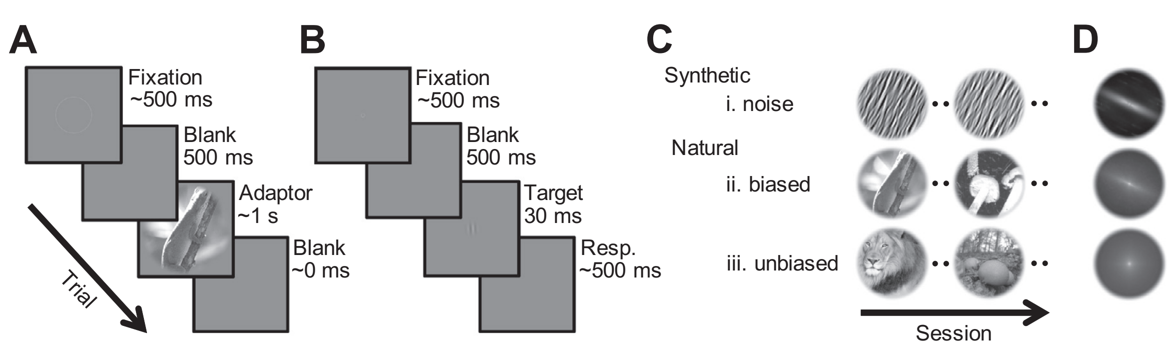

Fig. 1. Experimental design. Within session, adaptation trials with adaptors of a single type were randomly interleaved with target trials. (A) Adaptation trials were used to affect the perceived orientation by exposing observers to adaptors, either synthetic patterns or natural images (experimental differences summarized in Table 1). (B) Target trials were used to determine a perceived vertical orientation, by presenting observers with a near-vertical Gabor patch target, to which they reported whether the patch is oriented CW (clockwise) or CCW to vertical. (C) Example adaptors. (i) Oriented noise adaptors (‘noise’) are synthetic random $1/f^{\alpha}$ noise patterns that were filtered in order to depict the orientation content at a particular orientation. (ii) Biased image adaptors (‘biased’) are unmodified natural images selected according to criteria favoring content oriented at a particular orientation. (iii) Unbiased image adaptors (‘unbiased’) are unmodified natural images selected randomly. (D) Average of the two-dimensional Fourier power spectrum of adaptors. Because of selection, biased images had on average more Fourier power at the biased orientation (ii), similar to the Fourier power distribution of synthetic adaptors (i), whereas unbiased images had a natural distribution of Fourier-power (iii).