Experience can change the 'light-from-above' prior

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To interpret complex and ambiguous input, the human visual system uses prior knowledge or assumptions about the world. We show that the 'light-from-above' prior, used to extract information about shape from shading is modified in response to active experience with the scene. The resultant adaptation is not specific to the learned scene but generalizes to a different task, demonstrating that priors are constantly adapted by interactive experience with the environment.

The circular patches in **Figure 1a** have competing interpretations. However, patches that are brighter at the top are generally seen as convex and the others as concave, consistent with an assumption of light from above[1,2]. The Bayesian approach has successfully described performance in many perceptual tasks where stimulus information is combined with prior assumptions[3–5]. However, whether visual priors are hard-wired or learned in response to environmental statistics is not known[6]. We investigate the adaptability of the 'light-from-above' prior by adding shape information via haptic (active touch) feedback. We also test whether the same prior is used over a range of stimuli or adapted to specific situations and tasks.

Initially, each observer made convex-concave shape judgments of bump-dimple stimuli at different orientations to measure their pre-existing light prior. The peak of the light prior was inferred from the data fit (**Fig. 1b**). For all observers this was roughly overhead. The mean across observers was –1.3°, with a range across observers of –16.4° to 13.9°, where 0° is directly overhead. On average 56% of the stimuli were perceived as convex (blue area).

Visual-haptic training stimuli were consistent with a range of light source positions whose mean was shifted by either ±30° from the baseline prior for each subject. Visual stimuli with orientations within this new range were combined with haptic information indicating that the stimulus was a convex bump (**Fig. 1b**, red area). Other orientations were combined with concave haptic feedback. Thus, some stimuli previously judged as convex on most trials now felt concave, and vice versa. The ratio of convex to concave for each observer was held constant. Observers explored a set of stimuli for an unlimited time before judging the shape of a subsequent visual-only stimulus. As expected, haptic information disambiguated object shape during training (**Fig. 1b**, middle row). This was evident for all observers except one, also the only observer to display no training effect.

After training, observers judged a set of visual-only stimuli, identical to the baseline condition, to infer their post-training light direc-

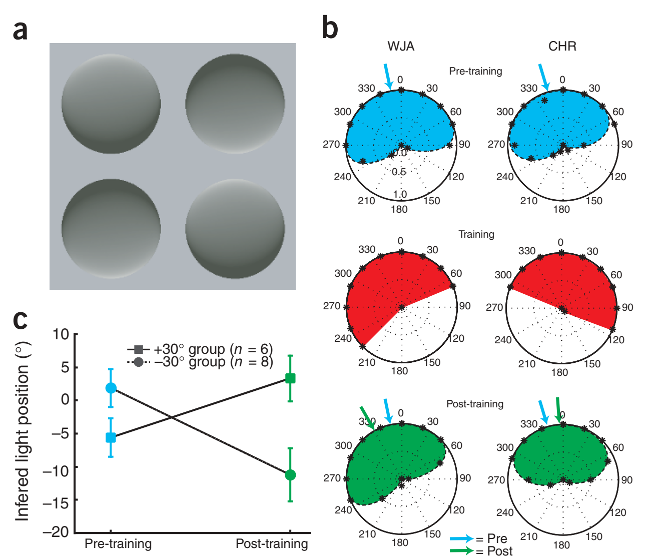

Figure 1 Stimuli and results for experiment 1. (**a**) Shading patterns consistent with squashed hemispheres (3.4° at 50 cm) illuminated by a single light source on a circle of 50-mm radius located 15 mm in front of the object. An eye patch eliminated binocular depth cues. In visual-only trials (pre- and post-training), four stimuli appeared for 3 s in square formation with their centers 5.6° from central fixation. Two orientations, 180° apart, were present in each trial in pseudo-random arrangement. A star indicated which stimulus to judge. Each orientation was judged 8 times in a 10-min block. On training trials, haptic information (PHANToM, SensAble Technologies force-feedback device, described elsewhere[10]) was consistent with smooth bumps or dimples of the same dimensions, on a smooth surface. A small dot indicated finger position. After the observer felt and observed all four stimuli, a central test stimulus appeared, visually identical to one of the previous four. The observer made a convex-concave judgment based on its visual appearance and then touched it. Each orientation was judged 12 times with 12 extra repetitions for orientations where haptics conflicted with the pre-training response, in a 1.5-h training session. (**b**) Data for two representative observers trained with opposite shifts. (0°) corresponds to stimuli brightest at the top. The proportion of stimuli perceived as convex (black stars) are fitted by a function based on two cumulative Gaussians (dashed lines) each centered at a concave-convex transition and whose average gives the light position prior (pre-training, blue arrow; post-training, green arrow). (**c**) Fitted pre- and post-light prior means for all 12 right-handed observers (10 naive, paid volunteers and 2 authors, W.J.A. and E.W.G.). The authors performed both training conditions, 2 weeks apart. Naive observers completed one. Error bars, ±1 s.e.m.

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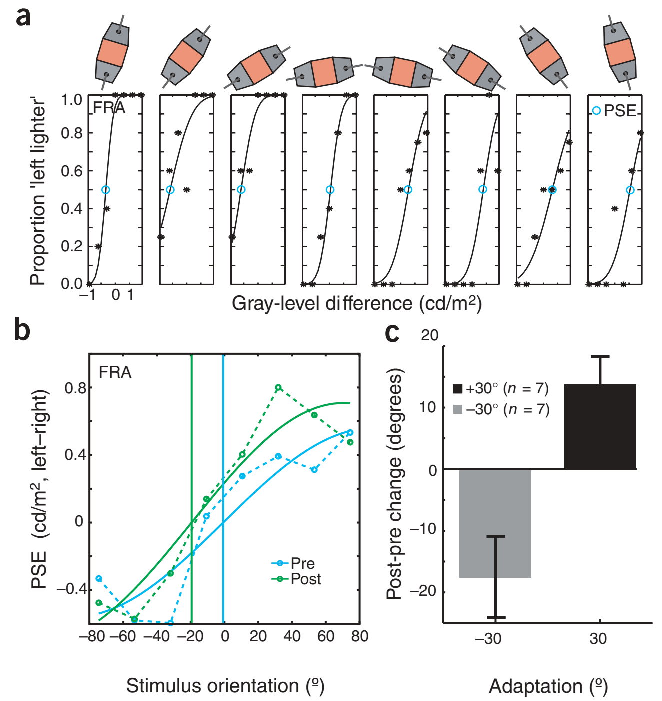

Figure 2 Stimuli and results for experiment 2 (**a**) Monocular control stimuli (top row) consisted of an orange square flanked by two gray quadrilaterals consistent with slanted square planes. The shape and 'cocktail stick' made the stimulus unambiguously convex. Gray levels of the side panels varied in opposite directions between 18.4 cd/m^2 and 20.3 cd/m^2 in 7 equal steps. There were 9 presentations at each of 8 orientations between –74° and +74°. The stimulus subtended 8° × 3.8° at the viewing distance of 50 cm. A 15-min block of control trials was completed pre- and post-training. Each plot shows pre-training data (stars) for a single stimulus orientation for one representative observer, fitted with a cumulative Gaussian (black curve). (**b**) PSE as a function of stimulus rotation for pre- (blue) and post-training (green). Data are fit by a fixed period (360°) sinusoid, consistent with assumed lambertian reflectance. Phase and amplitude are free parameters. Phase gives the stimulus orientation where equal intensity panels are perceived equally light, that is, the prior light source position (solid lines). (**c**) Mean change in inferred light position for all 14 observers. Three of the naive observers and the two authors (W.J.A. and E.W.G.) also took part in experiment 1. Error bars, ±1 s.e.m. Ethical approval was obtained from the Glasgow University Psychology Department and written consent was obtained from all subjects.

tions (**Fig. 1b**, green arrows). The group that trained with a +30° shift had an average shift of +8.9°; the –30° training group had an average shift of –13.1° (**Fig. 1c**). This training effect was highly significant (t_{13} = 7.049, $P < 0.01$) and remained significant after the two subjects who are authors of this paper were excluded (mean across conditions, 9.6°, t_9 = 5.479, $P < 0.01$).

Two possible explanations exist for the training effect. Observers may have implicitly learned that the average light source position had moved in the trained direction. In Bayesian terms, the observer's prior for light position had changed, resulting in changes in the perceived shape of the post-training stimuli. In this case, a crossover effect should be seen in a different task involving a light prior. Alternatively, observers may have directly learned the relationship between luminance pattern and shape or adopted a cognitive strategy to label objects as convex or concave. In this case, no crossover should be seen in a different task with different stimuli. To distinguish between these possibilities, we carried out a second experiment involving a lightness judgment task (stimuli shown in **Fig. 2a**).

Observers judged which of the two gray flanking panels was lighter. The stimulus orientation and the relative luminance of the panels changed from trial to trial. No explicit illumination information was present in the visual scene. However, each observer's point of subjective equiluminance (PSE) changed with orientation, in a way consistent with the stimulus being lit from above. With a stimulus orientation of –74° (left side below right), the left side was almost always perceived as lighter. At +74°, the left side (now at the top) was perceived more often as darker; the observer assumed that, for the two halves of the stimulus to have the same luminance, the upper half must be darker (in pigment) because it was receiving more light. Orientation was significant in a two-factor ANOVA ($F_{5.2,68}$ = 23.9, $P < 0.05$). Effects of surface orientation on perceived lightness have been found using stimuli containing implicit cues to illumination position[7]. Our study demonstrates that the visual system uses a light-from-above prior to recover lightness in the absence of any light-source information.

To identify any crossover effect, observers repeated the lightness judgments after completing the visual-haptic, bump-dimple training of experiment 1 (**Fig. 2b**). The group trained with a –30° shift had a mean shift in inferred light direction of –17.6°. The +30° training group had a mean shift of +13.8° (**Fig. 2c**). The 12 naive and 2 non-naive observers displayed similar shifts (means for naive subjects, –17.4° and +14.0°). This effect was significant ($F_{1,13}$ = 5.71, $P < 0.05$ as a main effect in a two-factor ANOVA). The effects observed in experiment 1, therefore, resulted from changes in the assumed light-source position. The second experiment implies that the visual system uses the same default light source position in quite different tasks, one involving shape and another requiring lightness judgments.

Unlike that of chickens[8], the human visual system can modify the 'light-from-above' prior. A short period of haptic training resulted in a substantial shift in inferred light position: 37% of the total introduced. Although visual learning can result in long-lasting effects[9], we would expect that our learned shift would disappear quickly as observers were re-immersed in the real world, where light comes predominantly from above. In conclusion, priors appear to be updated constantly in an adaptable system that monitors environmental statistics.

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COMPETING INTERESTS STATEMENT
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