# Report

# Depth Affects Where We Look

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## Summary

Understanding how we spontaneously scan the visual world through eye movements is crucial for characterizing both the strategies and inputs of vision [1–27]. Despite the importance of the third or depth dimension for perception and action, little is known about how the specifically three-dimensional aspects of scenes affect looking behavior. Here we show that three-dimensional surface orientation has a surprisingly large effect on spontaneous exploration, and we demonstrate that a simple rule predicts eye movements given surface orientation in three dimensions: saccades tend to follow surface depth gradients. The rule proves to be quite robust: it generalizes across depth cues, holds in the presence or absence of a task, and applies to more complex three-dimensional objects. These results not only lead to a more accurate understanding of visuo-motor strategies, but also suggest a possible new oculomotor technique for studying three-dimensional vision from a variety of depth cues in subjects—such as animals or human infants—that cannot explicitly report their perceptions.

## Results and Discussion

When we look at a visual scene for all but the briefest durations, we perform a series of ocular saccades that are driven by the current visual input and by higher-level cognitive states—and that in turn shape subsequent input to the visual system. Although an important goal in the field of active vision has been to understand how eye movements are determined from the interplay of bottom-up, stimulus-driven and top-down, task- and cognitive-driven factors [1–26], with a few exceptions [27–32] these studies have ignored a crucial visual variable: three-dimensional scene structure. Given the importance of extracting the 3D properties of scenes [33, 34], we examined the effect of 3D plane orientation on spontaneous eye movement.

Our subjects looked at planar surfaces inclined in depth—simulated on a computer screen via various depth cues—while we recorded their spontaneous exploratory eye movements. Each stimulus was presented for 3 s, during which subjects were told to look wherever they wished. Immediately prior to this, subjects fixated in the center of the stimulus, and following the presentation of the stimulus subjects reported the

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perceived 3D orientation of the plane. Stimuli were presented in circular windows in order to decrease any 2D anisotropy, as it is known that eye movements are attracted to objects' centers of mass [35]. Depth can be conveyed by any of a variety of depth cues [36], and in this experiment, stimuli were presented either monocularly or binocularly, with each eye's stimulus either a grid (containing linear perspective and texture gradient cues, but with grid lines uncorrelated with plane orientation), a texture gradient alone, or a random dot texture (containing binocular but not monocular depth cues), for a total of six combinations. The monocular dots stimulus was a control condition, because it was perceived as flat. Examples of stimuli are shown in Figure 1A. The extrinsic orientation of a plane can be specified with two parameters, and here we use slant and tilt angles, defined respectively as the angle between the plane normal and the direction toward the observer, and the direction of the projection of the normal onto the fronto-parallel plane (see [37] and Figure 1B for examples of surfaces with different tilts). Our stimuli had tilt that varied between 0° and 345° in steps of 15°, and slant that was always 45°.

Although our stimuli were presented inside circular windows, we found that the distribution of gaze was not isotropic. In fact, gaze distribution depended strongly on the 3D orientation of the stimulus. To illustrate this, we tabulated gaze density—the fraction of time spent looking at each point—from the onset of the initial saccade. In order to combine trials with different tilts, we rotated the gaze density of each trial to align the tilt with 90° (pointing upwards). The results for one subject are shown in Figure 2A, for the experimental and control conditions. In the experimental conditions, there is a strong maximum of gaze density along the tilt direction, or in other words, in the direction of fastest increase in depth. There is also some density along the entire axis corresponding to the depth gradient—i.e., in the direction of tilt $\tau$ but also $\tau + 180°$—but very little density in the other directions. This striking anisotropy is present in all five of the experimental conditions and in all subjects (see Figure S1 available online). In the monocular dots control condition, on the other hand, there is no favored direction, as we would expect.

The basic unit of exploratory eye movements is the saccade [38]. Therefore, in order to analyze our data in a more physiologically appropriate fashion, we extracted the saccades from eye movement data. To study how the saccades depend on the 3D geometry, for each saccade we calculated its direction: the orientation of the vector from its starting point to its endpoint. The distributions of saccade directions—again, aligned so that the tilt points upwards—are shown in Figure 2B for one subject; they are highly nonuniform, with peaks at 0° (the direction of tilt) and 180° in all but the control condition, in agreement with the densities shown in Figure 2A. Because saccade directions are circular variables, we use the Rayleigh test to test the nonuniformity of their distributions [39]. This test is based on the $R_0$ statistic, which varies from 1 (maximally peaked) to 0 (flat, or peaks that cancel). Because the distributions of saccade directions are bimodal with the two peaks separated by approximately 180° (as can be seen for one subject in Figure 2B, and is also the case for the other subjects, as seen in Figure S1), we used the axial version of the test, which treats
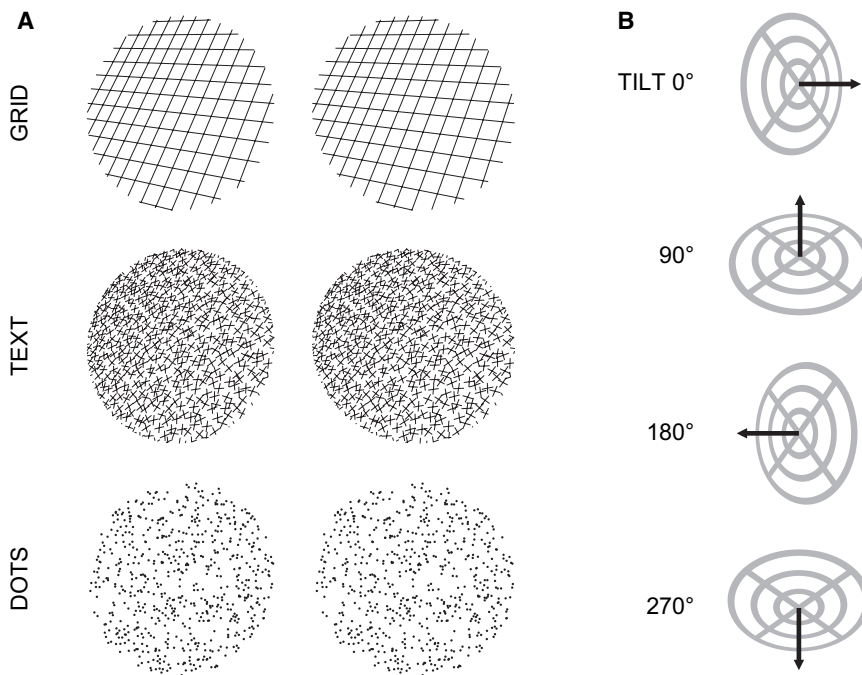
Figure 1. Examples of Stimuli

(A) Stereo pairs (for crossed viewing) of our three stimulus types: grids, texture gradients, and random dots. All three surfaces depicted have tilt 135°. Actual stimuli had texture twice as dense.
(B) Examples of surfaces with different tilts.

angles that differ by 180° as the same. The results of the Rayleigh test are shown in Table 1. All distributions are significantly peaked in all subjects, in all conditions other than the control. The peaks are strongest for the binocular stimuli, but are significant in all experimental conditions. By using a bootstrap test [40], we found that the tilt axis falls in the 95% confidence interval of the peak in all experimental conditions.

If we concentrate on just the first saccade of each trial in the experimental conditions, we can go further and make predictions of actual direction, rather than just the axis of the saccade. The direction distributions of the initial saccades are shown in Figure S2. As can be seen from these figures, compared to the corresponding distributions for all saccades (Figure 2B and Figure S1), the first saccades not only follow a definite axis (the tilt) but a vast majority have the same direction—the direction of increasing depth. For binocular stimuli, about 82% of the initial saccades are within 45° of the tilt direction (chance level is 25%; fractions for individual subjects 98%, 64%, and 86%, all significantly above chance at p < 0.001, binomial test). Another observation concerns the monocular texture stimuli: the first saccades show no significant peak in any of the subjects for these stimuli, contrary to the entire saccade sample that does. This may indicate that extracting 3D orientation from this cue is slow, and that the process is not finished in time to affect the first saccade.

We have shown that spontaneous eye movements are not isotropic, but tend to follow the axis given by 3D tilt. Initial saccades are even more predictable: a great majority follow the direction of tilt.

Before concluding that saccades truly depend on the 3D properties of the stimuli, we must first rule out confounding 2D factors. One such factor is the luminosity and spatial frequency gradients that are confounded with tilt direction in the grid and texture conditions. However, we can exclude this explanation because the strength of the effect is not significantly weaker in the binocular dots condition, where such gradients are absent. Another possible issue is the presence of lines in the grid condition: did saccades follow the 2D grid line

directions, and could this have mimicked our 3D effect? First of all, we rotated the grid texture on different trials, so there was little correlation between 3D tilt and grid lines. Second, we calculated the angle between each saccade and the nearest grid line and found that they were no closer than chance.

We can give two 3D geometrical interpretations of these results. Because the direction of tilt is also the depth gradient, one interpretation is that the initial saccade is directed so as to bring the gaze as far as possible from the observer (for a given amplitude), and subsequent saccades maximize depth changes (the depth gradient hypothesis). Another interpretation involves the shape of the stimulus: whereas the projection of the stimulus is a circle, its 3D shape is an ellipse, whose major axis projects precisely onto the tilt direction. Perhaps the subject's gaze is exploring the principal axis of the perceived 3D object (the principal axis hypothesis).

We wondered whether the predictable eye movement patterns that we found were really due to 3D orientation perception, or whether they could have been an artifact of the subsequent reporting task, which involved manual movements in adjusting a visual probe and may have resulted in hand-eye coordination [41]. We therefore performed a second experiment, which repeated the binocular conditions of the first experiment, except that the subjects had no explicit task to perform at all; instead, they were told to simply pay attention to the 3D stimuli. For comparison, subjects then performed a block with an explicit task.

When we analyzed saccade directions with respect to tilt, as in the previous experiment, we found that all three subjects had significant peaks in both the no-task and task conditions (p < 0.001), and in all cases tilt direction fell in the 95% confidence interval of the peak. Results are shown in Figure S3. For all subjects taken together, the peak was slightly smaller in the no-task (mean $R_0 = 0.38$) than in the task ($R_0 = 0.41$) condition, but this difference was not significant and did not attain significance for any subject. We conclude that the effect of 3D surface orientation on spontaneous eye movements can be obtained in subjects simply paying attention to a 3D stimulus and does not require the performance of or preparation for any particular task.

Although we have shown that 3D structure helps predict spontaneous looking behavior with simple planar stimuli, we were obviously interested in knowing whether our findings would generalize to more complex objects. We therefore performed a third experiment in which we showed subjects dihedral objects composed of two planes, with tilts that differed by 30°–180°. As in previous experiments, the objects were seen through a circular window, and the "spine" where the two planes met ran through the window's center. The objects
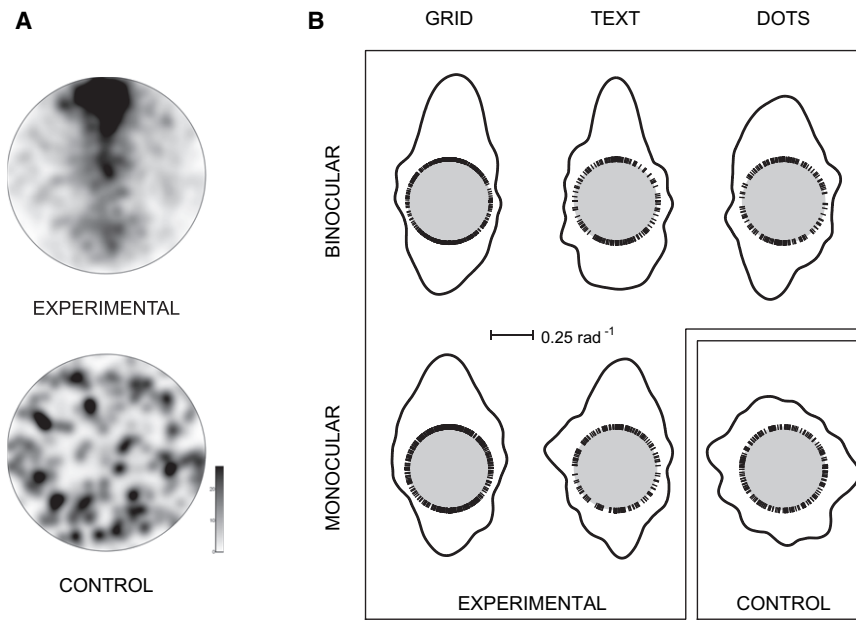
Figure 2. Results of the First Experiment for One Subject, SV

Corresponding figures for the other subjects can be found in the Supplemental Data.

(A) Gaze density—the fraction of time spent looking at each point, starting from the onset of the initial saccade. The darker a point, the more time subjects spent looking at it. Before averaging, densities for trials with different tilts were rotated to align the tilts with $90°$ (upward). Densities are shown for the five experimental conditions, in which depth cues indicated an inclined plane; and for the monocular dots control condition, in which the stimulus was a fronto-parallel surface. Densities were smoothed with a Gaussian kernel of width $0.5°$. The numbers on the gray scale denote gaze duration (as fraction of total) per radian$^2$ of stimulus area.

(B) The distributions of saccade directions (orientation of the vector from starting point to endpoint), presented for each of the five experimental conditions, and for the control condition. Saccade directions are rotated so that the tilt points upwards. For each direction (from the center of the gray circle), the radial distance of the black curve from the edge of the circle is proportional to the fraction of saccades having that direction, with the scale given by the bar. Individual saccade directions are marked on the rim. Distributions were smoothed with a quartic bell-shaped kernel of width $20°$.

could be either convex or concave and were presented with the binocular dot texture used in the previous experiments (see Figure 3A).

We analyzed the initial saccades of each trial by comparing their directions to the tilt of the plane that they landed on. (It would make no sense to compare to the tilt at the starting point, because these saccades start on or near the spine that separates the two planes.) The results for one subject are shown in Figure 3B, separately for convex and concave stimuli. For this subject, the peak is significant for convex ($R_0 = 0.48$, $p < 0.001$) but not for concave ($R_0 = 0.12$) stimuli. In fact, the Rayleigh test shows that the convex peak is significant for all three subjects (mean $R_0 = 0.46$), but that the concave peak is signficant only for one (but with the tilt direction outside the confidence interval of the peak; mean $R_0 = 0.15$). However, we have to be careful, because even saccades from the center to a random spot on the stimulus, when compared to the tilt at the landing point, will yield a peak at $0°$ for convex stimuli and $180°$ for concave ones. This is because for convex stimuli the tilt points, on the average, away from the center (see Figure 3A), and for concave stimuli toward the center. We therefore performed a permutation test to calculate this baseline, as well

as its confidence interval. We found that for convex stimuli, the value of $R_0$ was significantly higher than the baseline (for which mean $R_0$ would be 0.25) for all three subjects; for concave stimuli, on the other hand, $R_0$ was over baseline for only one subject (and in the latter case, the tilt direction did not fall within the confidence interval of the peak). Finally, we found that all three subjects had higher values of $R_0$ for convex than for concave stimuli; a bootstrap test revealed the difference significant in two, and in all three taken together. In analyzing the subsequent saccades from this experiment (saccades after the first one), we could find no evidence for alignment with the 3D orientation.

These results show that the correlation between spontaneous saccades and 3D surface orientation generalize to more complex objects. In the other experiments, we found that initial saccades are overwhelmingly in the direction of *increasing* depth. Together with this observation, the depth-gradient hypothesis predicts a greater dependence of saccade direction on tilt in the convex case, where saccades from the center along either of the tilt directions do indeed yield steepest depth increase. For concave stimuli, on the other hand, the depth at the gaze point is "trapped," so to speak, because tilt directions correspond to maximum depth *decrease*. As described above, we indeed found the predicted difference between convex and concave stimuli. We also tested the principal-axis hypothesis by calculating the principal axis directions of each of the two surfaces (which are partial ellipses in 3D), and whose directions always fall within about $15°$ of the central spine. We found little support for the principal-axis hypothesis: the saccade direction of only one subject had a significant peak in the direction of the principal axis, and in only one of the two conditions (concave).

### Conclusions

In three experiments, we have demonstrated that the directions of spontaneous, exploratory eye movements are strongly

Table 1. Results of Experiment 1 in Terms of the Nonuniformity Measure $R_0$

| Subj. | Bincoluar | | | Monocular | | |
| | Grid | Text. | Dots | Grid | Text. | Dots |
|---|---|---|---|---|---|---|
| CB | 0.32* | 0.45* | 0.45* | 0.30* | 0.13* | 0.07 |
| SV | 0.47* | 0.40* | 0.38* | 0.37* | 0.30* | 0.08 |
| VC | 0.55* | 0.47* | 0.51* | 0.47* | 0.27* | 0.16 |
| All | 0.46* | 0.44* | 0.44* | 0.36* | 0.22* | 0.04 |

Data for the three individual subjects, and all subjects together, in the six experimental conditions. Statistically significant results of the Rayleigh test, indicating that saccade directions are nonuniform ($p < 0.05$, Bonferroni correction for 6 conditions) are indicated by asterisk.
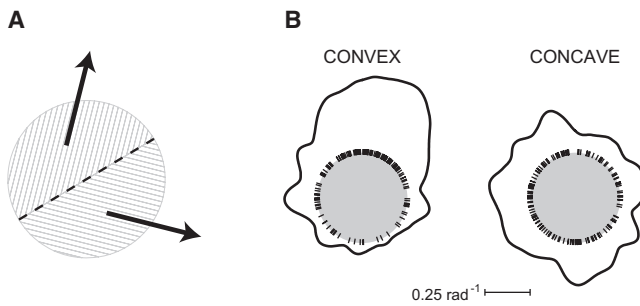
Figure 3. Stimuli and Results of Experiment 3

(A) A diagram illustrating object geometry in the two-surface experiment. Two inclined planes (shown by different hash marks) intersect at a central spine (dashed line). Tilt directions are shown as arrows. This is therefore a convex object, and we used both convex and concave objects. Actual stimuli were displayed as random-dot stereograms.

(B) Data from one subject, AB, in the two-surface experiment, showing the distribution of initial saccade directions, separately for convex and concave stimuli. Saccade directions are given with respect to tilt at the saccade endpoint, with zero upwards. Corresponding figures for the other subjects can be found in the Supplemental Data.

shaped by the three-dimensional structure of the visual scene. The first experiment showed that, for an inclined plane perceived through a variety of depth cues, the first saccade was very often in the direction of plane tilt, and subsequent saccades often followed the tilt axis. A second experiment showed that this effect could be obtained independently of any particular task the observer may have in viewing the surface. A third experiment showed that the 3D shape of a more complex stimulus also predicts eye movements, in a way that is somewhat more complex but compatible with the previous results.

Although previous studies have examined how visual, motor, and cognitive factors affect spontaneous eye movements, there are few published results on the effect of 3D shape on eye movements. The major exception is work on spontaneous vergence movements, which has shown that various depth cues portraying an object evoke spontaneous vergence movements correlated to those evoked by a real 3D object [28–32]. However, studies concerned with the effects of visual factors on *where* we look have examined only the effects of the *2D projection* of the visual scene—with one exception (see below). Building on the pioneering work of Buswell [1] and Yarbus [2] that showed that observers do not fixate random points in images, but concentrate the gaze on informative regions, the informativeness of image regions was quantified [3], and other studies showed that images evoke reproducible sequences of eye movements [4]. More recent findings of correlations between exploratory eye movements when viewing images and image features such as contrast, edge density, and two-point correlations [5–9] have inspired the popular saliency model for gaze shifts during image viewing [10, 11]. However, it has also been argued that saliency is often confounded with semantic informativeness [12], and that cognitive factors guide fixation at least as much as low-level image features do [13, 14]— although a study has shown that some high-level features are ineffective in guiding saccades [15]. Other strands of research have emphasized the role of eye movements in goal-directed behavior and sensorimotor routines [16–26]. The sole work we know to address the question of the effect of 3D shape on saccades shows that the precise endpoints of saccades to objects are influenced by the object's 3D shape [27].

We presented two hypotheses to describe the way in which 3D surface orientation affect eye movements: the depth-gradient hypothesis, in which the gaze moves back and forth along the depth gradient axis; and the 3D-shape hypothesis, in which the gaze moves along the principal axis of the perceived three-dimensional object. We can speculate on the computational advantages of the two strategies: for the depth-gradient strategy, the calculation of slant and tilt for a fixation is particularly simple, given the slant and tilt for a prior fixation on the same plane; the principal-axis strategy would ensure that the gaze be allocated to the most significant axis of an object's actual shape, rather than that of its projection. Be that as it may, although the third experiment offers some evidence in favor of the depth-gradient hypothesis and against the principal-axis hypothesis, the two hypotheses still need to be compared rigorously. Another question concerns the generality of our results: our stimuli demonstrate a 3D effect and were constructed on purpose to be neutral with respect to 2D stimuli such as saliency that have been shown to partially drive saccades as well [10]; both 2D and 3D factors are present in natural scenes, so it would be interesting to see how the effect of 3D orientation holds up in the presence of possibly conflicting saliency factors. We should point out that, although the grid stimuli in Experiment 1 had a very significant 2D feature, namely the grid lines, we found that saccades nevertheless followed the depth gradient rather than these lines.

There is perhaps an immediate application of our results. In Experiment 2, we have found the correlation between spontaneous eye movements and 3D structure even when subjects were not performing any particular task. We therefore propose the use of spontaneous eye movements to study 3D vision quantitatively in subjects in which we cannot probe it directly through explicit tasks, such as human infants or animals, in whom we can measure saccades.

**Experimental Procedures**

Stimuli were displayed on a monitor with fast phosphor (dot pitch 0.29 mm). For binocular stimuli, the monitor was covered by a screen (Z Screen, Stereo-Graphics) that alternated between circular polarizations every other frame (100 Hz), while the subject wore glasses with opposite polarized filters. Explicit responses were measured with a joystick. Eye movements were recorded with an infrared video eye tracker (EyeLink II, SR Research), operating at 500 Hz in pupil-only mode, with compensation for head movement [42]; recordings were monocular. Data from one session each in Experiments 1 and 3 were lost because of eyetracker problems. Subjects' head movements were restrained with a chin rest (placed so that the eyes were about 57 cm from the monitor).

Stimuli were of three types (grid, texture, and dots) and could be presented monocularly or with binocular disparity. They consisted of simulated surfaces passing through the center of the monitor, and inclined with respect to the monitor or fronto-parallel plane. Lengths will be given in terms of object features, before projection. Grid stimuli had 1 cm square cells. The angle between the tilt and the grid was 0°, 30°, or 60°. Texture stimuli consisted of crosses placed on the inclined plane. The arms of the crosses were of equal length (5 mm) and at right angles. The crosses were randomly oriented and were arranged on a square grid of 5 mm cell size and then randomly jittered by up to 1.25 mm. Dot stimuli were created by generating dots distributed uniformly in the image plane, with density 4 cm$^{-2}$, and projecting the dots onto the stimulus object. In the monocular condition, these stimuli therefore had flat depth cues. Stimuli were drawn in polar projection, with a simulated distance of 57.3 cm and interocular distance of 6.4 cm; were clipped to lie within a circle of radius 10 cm on the screen, with the rest of the screen black; and were preceded by a central fixation cross (length 1 cm).

Experiment 1, which had monocular and binocular stimuli of all three types, had tilts 7.5°, 22.5°,…, 352.5°. Experiment 2 had stimuli that were only binocular, but otherwise identical to those in Experiment 1. In

Experiment 3, which used only binocular dots stimuli, the tilts of the two planes were unequal and chosen from 15°, 45°,…, 345°. Convex dihedra were generated by selecting the farthest plane at each point, whereas for concave dihedra we selected the closest plane. The slants of all surfaces were 45°.

The stimulus was preceded by a central fixation cross (duration from 0.5 to 1 s), immediately followed by the stimulus (duration 3 s in Experiments 1 and 3, 5 s in Experiment 3). Subjects were told to fixate the cross while visible, and then explicitly told to look wherever they wished at the main stimulus. In Experiments 1 and 3, after the stimulus subjects adjusted a visual probe (Experiment 1) or probes (Experiment 3), consisting of concentric circles and radial spokes, in order to make it (them) parallel to the plane(s) perceived.

In Experiment 1, subjects performed 4 blocks of 120 trials each in random order, with monocular and binocular stimuli in separate blocks (order BMMB for 2 subjects, MBBM for the other). In Experiment 2, subjects performed 1 block of 120 trials without any explicit task, then 1 block with a task, as in Experiment 1. In Experiment 3, subjects performed 3 blocks of 132 trials each.

We extracted saccades from eye movement data by computing speed and applying a symmetric $5^{th}$ order Savitzky-Golay filter with width 40 ms [43]. Saccades were initially identified as contiguous time blocks where ocular speed exceeded 30°/s; their starting and endpoints were identified with a 10°/s threshold. Saccades separated by less that 100 ms were merged. Finally, any saccade of amplitude less that 1°, or falling within 4 ms of a blink (identified by the pupil size) was rejected.

Three subjects, naive to the goals and hypotheses of the experiments, participated in each of the three experiments, with none participating in more than one experiment. All had normal or corrected-to-normal vision (subjects that wore glasses or contact lenses did so during the experiments), and none had any known visual, neurological, or oculomotor impairments. All subjects gave informed consent.

### Supplemental Data

Supplemental Data include four figures and can be found with this article online at http://www.current-biology.com/supplemental/S0960-9822(08)01429-2.

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