

Lightness perception for surfaces moving through different illumination levels

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Lightness perception has mainly been studied with static scenes so far. This study presents four experiments investigating lightness perception under dynamic illumination conditions. We asked participants for lightness matches of a virtual three-dimensional target moving through a light field while their eye movements were recorded. We found that the target appeared differently, depending on the direction of motion in the light field and its precise position in the light field. Lightness was also strongly affected by the choice of fixation positions with the spatiotemporal image sequence. Overall, lightness constancy was improved when observers could freely view the object, over when they were forced to fixate certain regions. Our results show that dynamic scenes and nonuniform light fields are particularly challenging for our visual system. Eye movements in such scenarios are chosen to improve lightness constancy.

Each of the factors confounded in the light reaching the eye contributes to the lightness judgment, leading to systematic deviations of the percept from constancy that are usually consistent with the surface brightness. For example, when participants were asked to discriminate the reflectance of real objects under different illuminations, they produced errors compatible with brightness-based judgments (Robilotto & Zaidi, 2004). Similarly, observers are unable to account for the scene geometry in order to discount the effect of surface orientation, even though they can accurately estimate the slant of the surface (Boyaci, Maloney, & Hersh, 2003; Ripamonti et al., 2004). Eye-movement experiments showed that the perceived shade of a surface depends on its luminance distribution, in this case dictated by the specific sampling of fixations (Toscani, Valsecchi, & Gegenfurtner, 2013a, 2013b, 2015).

The visual system also has the remarkable ability to produce a single lightness match for a surface of uniform reflectance even when it is placed under variable illumination. Lightness perception under such circumstances is based mainly on the brightest part of the surface (Zdravković, Economou, & Gilchrist, 2006). Furthermore, we observed a strong relationship between the fixated regions and the lightness judgments and we have demonstrated the causal nature of this relationship using a gaze contingent paradigm. Simulations with rendered physical lighting showed that brightest regions of shaded objects are particularly informative about their surface albedo. Therefore, a sampling strategy favoring the brightest parts of a surface's luminance distribution—as an estimator for

Introduction

The amount of light reflected from a surface depends not only on the reflective properties of the material itself, but also on the illumination intensity and the geometry of the surface. When reflected light reaches the eye, all of these factors are confounded. Nevertheless, humans are quite consistent in their surface reflectance judgments—a visual phenomenon called lightness constancy (Adelson, 2000; Gilchrist, 2006). Although the correspondence between material property and perceived shade is quite compelling, the visual system can only partially achieve lightness constancy.

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the surface reflectance—represents an efficient and simple heuristic for the visual system to achieve accurate and invariant judgments of lightness (Hermens & Zdravković, 2015; Toscani et al., 2013a).

In order to estimate the reflectance of a surface and thus perceive its lightness, the visual system has to process the luminance distribution of that surface. This distribution changes with the illumination conditions, and when the visual system fails to discount the illumination from the luminance distribution we observe constancy failure: objects appear darker in a dim light and lighter in a bright light (Ripamonti et al., 2004; Robilotto & Zaidi, 2004). Such failures are frequently observed in the laboratory, even though real life offers ample experience of familiar objects being viewed and manipulated under different illumination intensities. Therefore, this naturalistic scenario was realized in the laboratory, where a flat gray surface was manually moved from spotlight illumination to a shadow right in front of the observers (Zdravković, 2008). Even in such situations, the luminance distribution biased lightness perception and produced constancy failures that went into the direction of brightness matches.

Here, we extend this earlier study to allow for a full control of the dynamics of the target and the dynamics of illumination change. Rather than moving the stimulus by hand from one illuminant to another, we use rendered scenes with three-dimensional (3D) targets and a gradual change in illumination over time. Our paradigm allowed us to investigate the detailed time course of lightness constancy and its potential failures, rather than a comparison between two different static illumination conditions. In order to investigate the role of fixations on lightness perception of a moving surface, eye movements were recorded and manipulated. This enables us to simultaneously focus on the temporal and spatial characteristics of lightness perception.

General method

Participants

All four experiments were conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving human subjects. Participants were informed about their experimental task and their rights, and they provided written informed consent. All observers had normal or corrected-to-normal visual acuity and they were all naïve to the purpose of the experiments and our specific hypothesis. Given that this was a lightness experiment we did not control for color vision deficiencies.

Every participant took part in only one of our experiments and was run individually. There were six participants in Experiments 1 and 3, and four participants in Experiments 2 and 4.

Display and apparatus

A Dell Precision 380 computer (Dell Inc., Round Rock, TX) running Microsoft Windows 7 controlled the experiment and the stimulus presentation. The scenes were rendered with the physically based rendering software, Radiance, and interfaced with a MATLAB toolbox (Lichtman, Xiao, & Brainard, 2007). The movies were composed of individual frames, each containing the rendered target surface in the successive points of its target trajectory.

Display scene

The display used in all experiments of the current study contained a scene with: (a) the target, a pendulum-like surface that could move across an illumination field defined by a gradient, and (b) a set of static objects placed in these different illumination levels created by the gradient (Figure 1A).

The scene, covering $34^\circ \times 63^\circ$ of visual angle, was presented on a calibrated Eizo ColorEdge CG245W monitor (22 inches, 1920×1200 pixels resolution, 60 Hz refresh rate, 10 bits per color channel; Eizo Inc., Cypress, CA). The CIE xyY color space chromatic coordinates of the three RGB channels of the monitor were: $R = (0.6527, 0.3309, 34.8052)$, $G = (0.2017, 0.6804, 70.1604)$, $B = (0.1504, 0.0661, 8.9073)$.

Target

The pendulum appeared to be in a gray room, dimly illuminated from the upper left corner. It occupied approximately $20.5^\circ \times 9^\circ$ of visual angle along its major and minor axis, respectively. It looked as if the pendulum was hanging from a cylindrical segment that was secured above the scene.

The dynamics of the target surface are presented in Figure 2A. In the moving conditions, the surface moved only in one direction, from one side of the virtual scene to the other. This movement took 8 s (frequency: 0.0625 Hz). The length of the segment was 21.2° of visual angle, while the speed of the pendulum was characterized by an acceleration A , where $A = l \sin \alpha$, α could be in the interval of $[-35^\circ, 35^\circ]$, and l was 27° . This was chosen to simulate the actual physical motion of a simple pendulum.

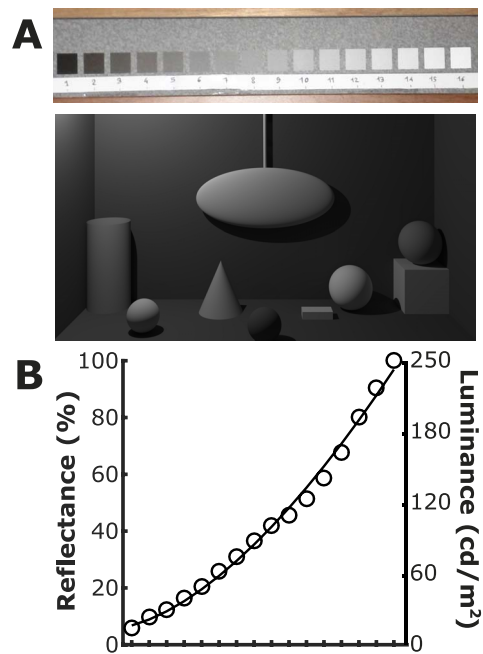


Figure 1. Display and scale. (A) The display used in the experiments. A pendulum surface was embedded in a gray box containing a number of simple geometrical objects (see Scene layout). A matching scale was located in a wooden box on top of the experimental screen, with values under the gray chips. (B) Measured reflectance and luminance values for the matching scale chips.

The pendulum surface was rendered completely matte, so the light it reflected is given by the Lambert cosine law. The surface was rendered with three different reflectance values (35%, 50%, 65%) to create variability and prevent participants from choosing the same response throughout the experiment. It gave the subjects the impression that the pendulum was of a different reflectance in different trials. The average luminance of the pendulum surface varied from 4, 6, and 8 to 24, 34, and 44 cd/m^2 , for the low, middle, and high reflectance, respectively. The luminance distribution of the surface was positively skewed and, consequently, its average was higher than the median and among the brightest values (Figure 2B). Luminance levels of the images were measured using a Photo Research PR650 spectroradiometer (Photo Research, Syracuse, NY) with a spatial resolution of 1° of visual angle.

Scene layout

The pendulum was “hanging” above a set of eight geometrical objects that appeared to be 3D and placed on the room floor. They were rendered to have the following reflectance and luminance values, as shown in Figure 1A, from left to right: *cylinder*, mean luminance = $5.8 \text{ cd}/\text{m}^2$, median = $5.34 \text{ cd}/\text{m}^2$, range = $[0.07 \text{ } 13.8] \text{ cd}/\text{m}^2$, reflectance = 75%; *sphere*, mean luminance = 10

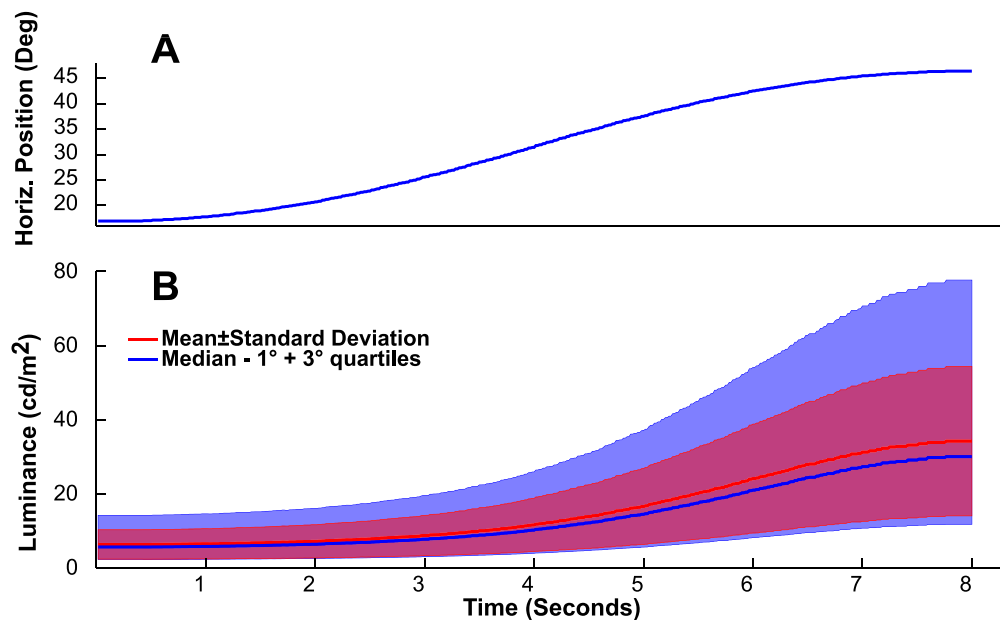


Figure 2. Dynamics of the target and its luminance distribution. (A) The horizontal position of the center of the moving pendulum surface is plotted on the y-axis and time is represented on the x-axis. (B) Luminance distributions evolving over time for the 50% reflectance surface. The mean and the standard deviation of the surface for every time point is depicted in red, the thick red line represents the value of the mean and the red area represents the values between the mean \pm SD. The median is represented in blue again as a function of time. The blue area represents the values between the Median + Third Quartile and Median – First Quartile.

cd/m², median = 7.46 cd/m², range = [0.51 29.25] cd/m², reflectance = 100%; *cone*, mean luminance = 9.52 cd/m², median = 10.14 cd/m², range = [0.95 18.39] cd/m², reflectance 50%; *sphere*, mean luminance = 1.21 cd/m², median = 0.86 cd/m², range = [0.1 3.75] cd/m², reflectance = 10%; *cube*, mean luminance = 9.1 cd/m², median = 4.33 cd/m², range = [3.78 16.86] cd/m², reflectance = 75%; *sphere*, mean luminance = 11.28 cd/m², median = 10.28 cd/m², range = [0.92 26.79] cd/m², reflectance = 60%; *cube*, mean luminance = 4.41 cd/m², median = 3.08 cd/m², range = [0.96 18.39] cd/m², reflectance = 70%; and *sphere*, mean luminance = 3.04 cd/m², median = 2.88 cd/m², range = [0.3 6.7] cd/m², reflectance = 30%. The walls were rendered to have a 10% reflectance (mean luminance = 2.85 cd/m², median = 1.95 cd/m², range = [0.01 27.8] cd/m²). The light source responsible for the gradient was placed at the top left of the center of the scene and was not visible from the observer's point of view. Another light source was placed far behind the observer's point of view to ensure a certain level of ambient illumination.

Matching scale

A lightness matching scale (Figure 1A) was located in a wooden box placed on the top of the experimental computer screen. The scale had 16 different gray squares printed in order of increasing reflectance against a white noise background texture in gray-scale. The reflectance values (R) of individual chips (shown in Figure 1B) are described by the following exponential relationship: $R = x^{1.627} + 5.78$ where $x = (1, \dots, 16)$. The exponential nonlinearity was chosen to make the chips perceptually equidistant with respect to lightness. Assuming the white chip reflected 100% of the incoming light, the luminance of each of the 16 chips (L) is given by $L = 251 R$ cd/m².

The scale was illuminated by a fluorescent lamp (CIE xyY = 0.3721, 0.3684, 41.15) that was placed at the top of the box and was not visible to the observers. The experimental computer controlled the light via an audio board. The matching scale was not illuminated when the virtual scene was shown on the computer screen. Its illumination automatically turned on at the end of each trial and stayed on for 5 s in order to keep the light adaptation of observers constant. After the light was turned off, observers would indicate the sample from the scale that best matched their lightness percept. To do so, they would click, using a mouse, on a number line with the values 1 through 16 presented at the top of the experimental screen directly below the corresponding matching chips of the scale (see Figure 1A).

We asked our observers to “pick the chip painted with the same shade of gray as the target surface in the

virtual scene.” The presence of two different light fields and the instructions were designed to induce the observers to produce their matches in terms of lightness (perceived surface albedo) instead of brightness (perceived surface luminance; Arend & Goldstein, 1987; Arend & Reeves, 1986; Arend & Spehar, 1993).

Procedure

The experiments were run in a dark room. Participants had their heads stabilized by a chinrest with the distance between forehead and the center of the screen set at 38 cm.

Eye tracking procedure

Gaze position signals were recorded with a head mounted, video-based eye tracker (EyeLink II; SR Research, Ottawa, ON). Gaze position signals were sampled at 500 Hz and monitored in real time. At the beginning of each experiment, the *eye tracking* system was calibrated and at the beginning of each trial, the calibration was re-examined: if the error was more than 1.5° of visual angle, a new calibration was performed; otherwise, a simple drift correction was applied. To compute fixation error, one fixation dot was presented on the screen and the fixation position reported by the eye tracker was compared with the actual position of the dot on the screen. The position of the dot was randomly sampled from a region centered within the screen (from 6° to 57° horizontally and from 3° to 31° degrees vertically; where (0°, 0°) is the bottom left corner of the screen).

Experimental design

In all our experiments we tested four conditions for the pendulum surface: (a) the surface remained stationary for the whole duration of each trial in the light side of the light field (L), (b) surface remained stationary in the dark part of the light field (D), (c) surface moved from the light to the dark side of the light field ($L > D$), and (d) surface moved from the dark to the light side of the light field ($D > L$). In Experiment 3 we only tested conditions $D > L$ and $L > D$, but the surface could disappear before the full motion sequence was completed. We also manipulated the observers' fixation pattern using a gaze contingent paradigm (Toscani et al., 2013a, 2013b, 2015). These manipulations are explained in detail in the individual experiment descriptions. In all the experiments, the different conditions were randomized across trials.

Experiment 1: Free looking

In the first experiment, we wanted to measure lightness perception and lightness constancy under natural conditions. We used a rendered virtual scene, in which a 3D object moved through an articulated environment. These presentation conditions provide a rich context with different illumination levels due to the light-field gradient and are presumed to favor lightness constancy (Gilchrist & Annan, 2002). The use of a large number of surfaces with different reflectances should prevent the Gelb effect (Gelb, 1929) from occurring.

Methods

In these conditions, we collected behavioral data (i.e., observers performed the lightness matching task) and we collected fixation data from eye tracking. Our observers were allowed to freely explore the scene.

Task

We presented the scene (as depicted in Figure 1A) to our observers, in the four different conditions listed above. Each trial lasted 8 s, after which the scale was illuminated for 5 s and observers were invited to perform a lightness match. They were explicitly instructed to pick only one sample from the scale. They were told that the chosen chip should most closely resemble the shade used to paint the pendulum surface in the virtual scene.

Participants produced 10 matches for each of the three reflectance values and each of the four conditions, making for 120 matches in total ($10 \times 3 \times 4$).

Results

In the case of perfect lightness constancy, lightness matches in the conditions (D) and (L) should not differ, whereas any failure in discounting the illumination should result in darker matches in the condition (D), replicating classical findings (Katz, 1935). The prediction for the two moving conditions ($L > D$ vs. $D > L$) is less obvious. In both conditions, the presented frames are the same; the only difference is in the temporal order of presentation. As a result, any difference in the matches needs to be interpreted as an effect of the time sequence.

Matching

Matching results are shown in Figure 3. The data (averaged for each observer for each condition and

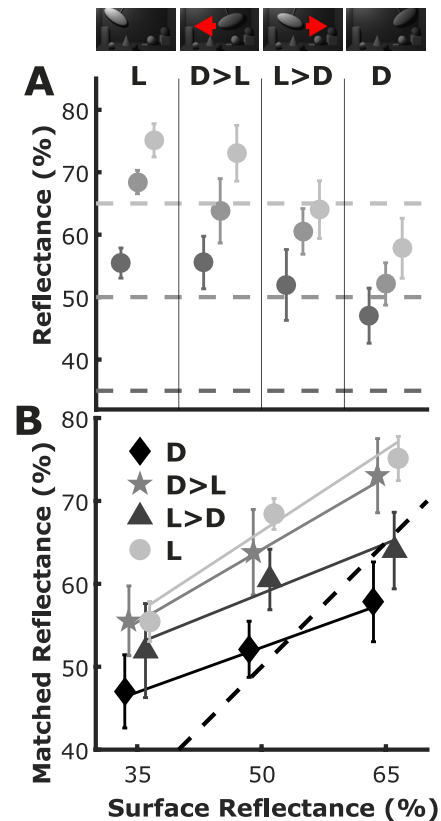


Figure 3. Lightness matches in the free looking paradigm. (A) The graph depicts average reflectance and standard error for the chosen gray samples (gray circles with error-bars). The x-axis stands for experimental conditions, indicated by the icons on top and the labels on the bottom; the y-axis is measured reflectance. The three gray shades of the data points represent the three reflectance values of the target; the horizontal dashed lines represent the reflectance values used to render the target using the same shades of gray as the data points. (B) Average reflectance and standard error for the chosen gray samples (y-axis) as a function of the virtual surface reflectance (x-axis), for the four conditions (different symbols and colors).

each reflectance) for the stationary (L and D) and moving conditions ($D > L$ and $L > D$) were analyzed separately with 2×3 (Condition \times Reflectance) two-way repeated measures ANOVA.

In both cases, no significant interaction was found, $F_s(2, 10) < 3.59$; $p_s > 0.05$, but the main effects of condition, $F_s(1, 15) > 35.85$; $p_s < 0.005$, and surface reflectance, $F_s(2, 10) > 7.21$; $p_s < 0.05$, were significant. The significant effect of surface reflectance indicates that the different reflectance levels, chosen to render the surface, were actually perceived by the observers and were used to provide the lightness matches. Since no interactions between surface reflectance and condition were found significant, the matching data were averaged over reflectance.

The matches for the L condition were compared with the D condition in a paired t test, $t(5) = 4.93$, $p < 0.005$,

and revealed that when the surfaces remained stationary in the lighter side of the virtual scene (L), they were matched with a lighter patch on average than when they remained stationary in the darker side of the scene (D). This result means that the visual system is not capable of fully discounting the illumination, despite the richness of the visual scene in which the target surface was embedded. This finding is analogous to what we previously found with real stimuli (Zdravković, 2008), suggesting that our rendered scene is comparable to a real one with respect to the experimental question.

A t test was also performed to compare the conditions where the target moved from the dark to the light side of the virtual scene ($D > L$) and vice versa ($L > D$). The test revealed that the matches were on average higher in the $D > L$ condition, $t(5) = 2.68$, $p < 0.05$. Given that the visual information provided to the visual system was constant in the two conditions (i.e., the observers were presented with the same video frames), and only the time order was different, this result means that the temporal order of the change in the luminance distribution of the moving surface has an impact on lightness perception. The target looks darker when it moves to the dimmer part of the scene, suggesting that the most recent points in time are likely to be more heavily weighted than the earlier ones.

Fixations

We have previously shown that when people are asked to judge the lightness of a surface in variable illumination, they tend to focus their fixations on the surface's brightest parts (Toscani et al., 2013a, 2015). However, this was shown for static targets, though it is well established that a dynamic context has a strong effect on fixation behavior (Dorr, Martinetz, Gegenfurtner, & Barth, 2010; Itti & Koch, 2000; for review, see Schütz, Braun, & Gegenfurtner, 2011). We therefore wanted to know whether the strategy we observed in the static lightness tasks is also applied in the dynamic conditions.

Figure 4 shows the fixation heat maps for the four conditions. In all of them, observers mostly fixated the pendulum surface, with a minor focus on the other objects in the scene and the background. In the moving conditions, people tended to follow the pendulum surface. They produced more fixations in the right (dark) side of the scene than in its left (light) side. A 2×2 repeated measures ANOVA with Side (left and right) and Condition ($D > L$ and $L > D$) as factors, revealed a significant main effect of Side $F(1, 5) = 17.71$, $p < 0.001$, no effect of Condition $F(1, 5) = 0.79$, $p = 0.42$, and no interaction, $F(1, 5) = 1.1$, $p = 0.34$. It is possible that observers needed more time in dim regions of the scene because it is more difficult to retrieve information

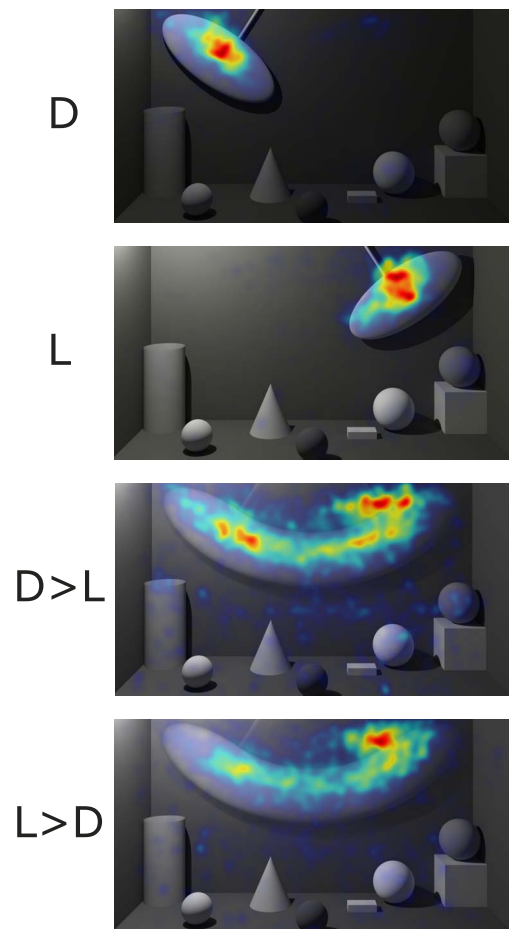


Figure 4. Heat maps in the free looking paradigm. Fixation distributions in each of the four conditions, averaged across frames and observers. Red areas are the most fixated, followed by yellow, green, and blue. Observers concentrated their fixations on the target (i.e., the pendulum surface).

from the low visibility area (Paulun, Schütz, Michel, Geisler, & Gegenfurtner, 2015). Our focus here is to compare these results with those of our previous studies. Therefore, we focused our analysis on the fixations that landed on the moving surface.

We first investigated the regions of the surface that fixations landed on. Every fixation position was expressed in vertical and horizontal coordinates along the minor and major axis of the ellipsoid that defines the surface. Figure 5 shows the fixated positions on the surface in the moving ($D > L$ and $L > D$) and in the stationary (L and D) conditions. Considering the horizontal axis of the surface for the moving conditions (Figure 5A), fixations tended to land on the center of the surface, with no substantial differences between the two moving conditions. The only qualitative difference between the two moving conditions is observed at the beginning of each cycle, where in the $D > L$ condition, fixations landed on average to the right of the center and in the $L > D$ condition, fixations landed to the left of the center.

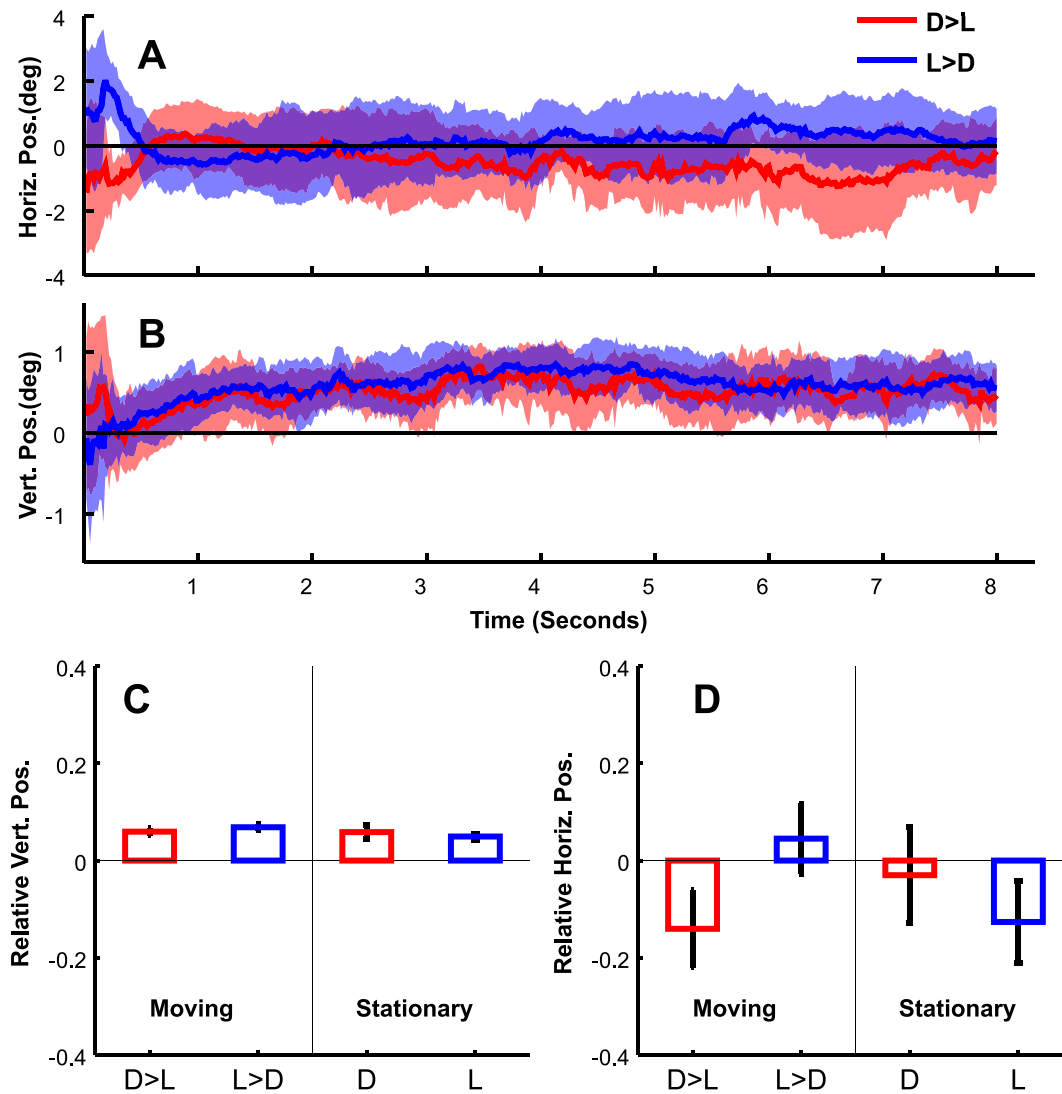


Figure 5. Fixations on the surface in the free looking paradigm. Fixation positions are projected on the minor and major axis of the surface ellipsoid, thus resulting in a vertical and horizontal position for every fixation, respectively. (A–B) Horizontal (A) and vertical (B) fixated positions (degrees of visual angle) on the surface during the two moving conditions: $D > L$ (red) and $L > D$ (blue). The fixated positions were averaged across observers and plotted as a function of time. The colored areas surrounding the averages represent the standard errors of the means. (C–D) Average over time of vertically (C) and horizontally (D) fixated relative positions (degrees of visual angle) on the surface. The fixated positions projected on the ellipsoid axes are expressed relative to the total length of each axis, with 0 being the center and -1 and $+1$ being the extremes.

This might be a consequence of the initial location of the fixation dot, which was placed at a random position within the inner region of the screen, on average corresponding to the center of the screen. A quick strategy to move one's gaze to the surface would be to look at its closest point, which would, on average, be shifted to the right in the $D > L$ condition and to the left in the $L > D$ condition.

Our main interest was to test the observers' strategy to focus on the most illuminated regions of the surface. Therefore, we averaged the fixated positions across time for every observer and we tested whether these average positions were significantly different from the

vertical and the horizontal center of the surface (Figure 5C and 5D, respectively). The horizontally fixated positions did not differ from zero in any of the conditions, $t(5) < 1.77$, $p > 0.1$, whereas the vertically fixated positions on average landed at the top of the surface, both for the stationary, D : $t(5) = 3.96$, $p < 0.05$, and L : $t(5) = 8.04$, $p < 0.001$, and for the moving conditions, $D > L$: $t(5) = 7.59$, $p < 0.001$, and $L > D$: $t(5) = 11.04$, $p < 0.001$. Since the illumination is coming from the top left of the virtual scene, these results mean that although observers tended to fixate the horizontal center of the surface, they still showed a preference for the better illuminated areas on its top side. If this is

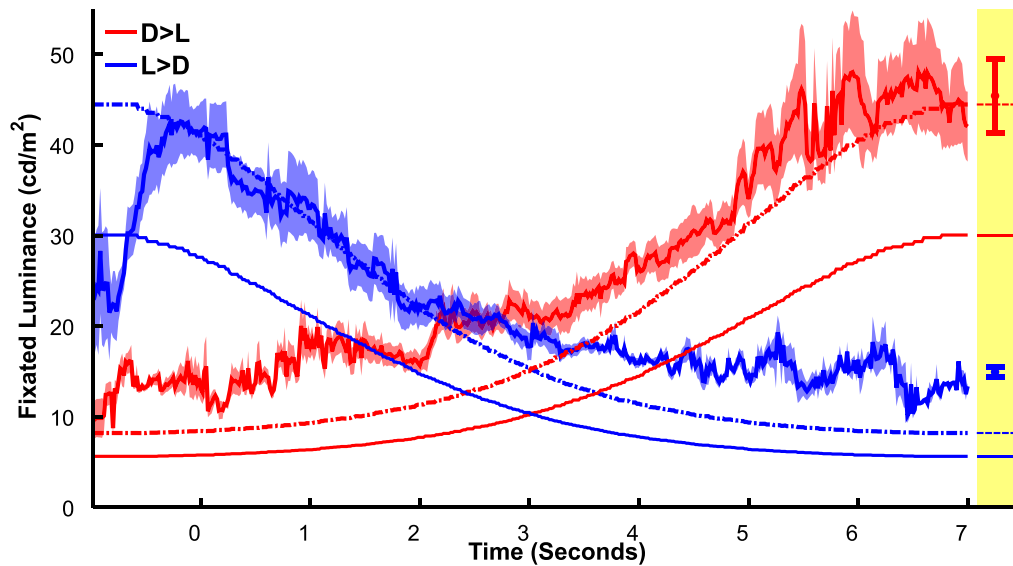


Figure 6. Fixated luminance in the free looking paradigm. For every fixation position that landed on the surface, the corresponding luminance emitted from the screen at that point was computed. The average across observers of those luminance values for every frame of the moving conditions ($D > L$, red; $L > D$, blue) is plotted as function of time; its standard error is represented by the red and the blue areas. The dashed lines represent the means of the luminance distributions in the two conditions and the continuous lines represent the medians. Average fixated luminance values for the stationary conditions are plotted (with their standard errors) in the yellow shaded region on the right (L , red; D , blue).

true, the luminance of the fixated regions of the surface should be higher than the central values of its luminance distribution. Given that at any time point, the luminance distributions of the surface are positively skewed, the median is a better estimator of their central luminance values than the mean, which is shifted into the upper range of the distribution.

In addition, for every fixation position on the surface, we computed the corresponding luminance emitted by the screen from that point (Figure 6). These fixated luminance values tended to be higher than the median of the luminance distributions at every time point. The only exception that was noticeable was during the beginning of the time sequence in the $L > D$ condition, possibly again because of the initial fixation point. A similar qualitative trend is also noticeable in the $D > L$ condition, but the fixated luminance is still clearly above the median, consistent with the fact that the gradient on the surface is lower when the surface is placed in the dark part of the virtual scene; therefore, a similar displacement in the horizontal fixated position between the two conditions ($L > D$ and $D > L$) could have a lower impact on the fixated luminance.

The fixated luminance values averaged over time were compared with the median (also averaged over time) and t tests revealed that observers fixated points that had a higher luminance than the central values of the luminance distributions for the surface, both in the moving, $D > L$: $t(5) = 5.91$, $p < 0.005$; $L > D$: $t(5) = 7.37$, $p < 0.0001$, and in the stationary conditions, L : $t(5) = 3.77$, $p < 0.05$; D : $t(5) = 17.11$, $p < 0.0001$.

In summary, participants tended to look at the target. They tended to focus their fixations on the top of the surface while maintaining their gaze on the horizontal center of the surface. Since the light source in the virtual scene was placed in the top left of the scene, looking at the top of the surfaces corresponded to fixations on well-illuminated parts of the surface. This result confirms our previous findings with stationary natural surfaces (Toscani et al., 2013a). In our previous study (Toscani et al., 2013a), we proposed that looking at the most illuminated parts of the surfaces supports lightness constancy. The same logic applies here. More importantly, it also shows the significance of this strategy since the introduction of motion did not alter eye-movement patterns.

This last finding is surprising, given the known effects of motion cues on fixation patterns. Therefore, we wanted to address the impact of this fixation strategy on lightness perception to understand their potential functional role in dynamic scenes, so in Experiment 2, we constrained fixation positions on specific regions on the target.

Experiment 2: Forced looking

Since people showed a tendency to fixate the part of the object with a luminance at top part of the luminance distribution of the surface, the fixation

strategy on the surface was manipulated in order to investigate its potential role on lightness appearance.

Methods

Experiment 2 was a complete repetition of Experiment 1, except that the participants were instructed not to view the display freely, but to constantly keep their gaze on a fixation dot. The locations for the fixation dot were selected from the horizontal axis of the ellipsoid, one point was 8° to the left of the horizontal center of the surface and the other was 8° to the right (76% displacement along the horizontal axis). Because of the illumination gradient, the point on the left was always lighter (light fixation condition) than the one on the right (dark fixation condition), although the luminance difference varied with the position of the surface in the virtual scene (from 4 to 51 cd/m^2). When observers fixated 3° away from the surface and thus failed to maintain fixation, the trial was repeated.

For each of three reflectance conditions, two fixation conditions, and four motion conditions, each observer produced five matches, giving 120 matches in total.

Results and discussion

Matching results are presented in Figure 7A.

A 2×4 repeated measures ANOVA, with fixation (dark and light) and motion condition (L , $D > L$, $L > D$, D) as factors, revealed a significant interaction, $F(3, 9) = 13.07$, $p < 0.005$, as well as both main effects, $F(1, 3) = 20.87$, $p < 0.05$, and $F(3, 9) = 15.94$, $p < 0.001$. The interaction comes from the fact that there is a large effect of the fixation position on the L and $D > L$ conditions, and basically no effect in the D and $L > D$ conditions. This interaction was significant also after restricting the ANOVA to the moving conditions, $F(1,3) = 14.48$, $p < 0.05$. If the effect of fixation position depends on the luminance difference between the fixated positions, it follows that the effect is larger in L than in D . Similarly, since in Experiment 1, we learned that the last moments in the time sequence were more weighted than the rest of the time sequence, it was not surprising to find much larger effect in the $D > L$ than in the $L > D$ condition.

Figure 7B represents the effect of fixation position as the difference between the matches in the light fixation and the dark fixation conditions and as a function of the difference in the fixated luminance across the two conditions. The two variables are linearly related in the conditions where the surface is not moving and the difference in fixated luminance does not change over time; see Figure 7B, regression line: $r^2 = 99\%$, $t(4) = 18.2$, $p < 0.001$. In the moving conditions, the

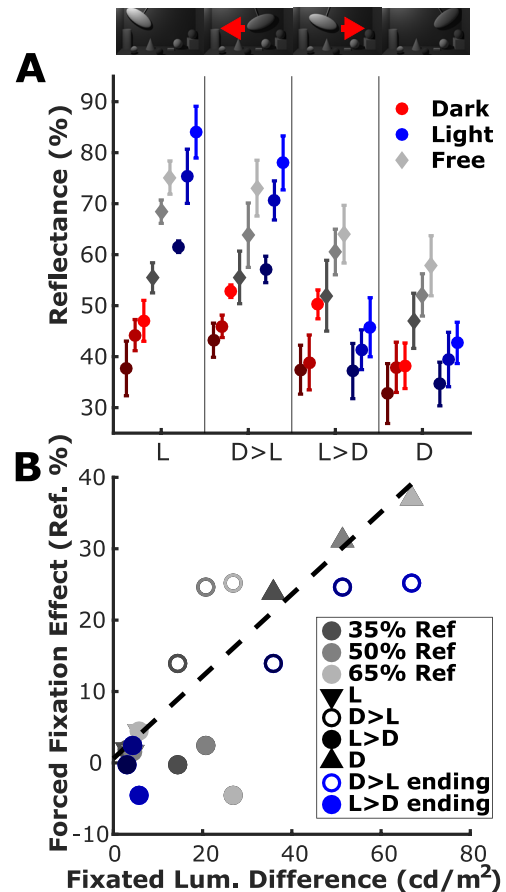


Figure 7. Lightness matches in the forced fixation paradigm. (A) Lightness matches averaged across reflectance. The mean across observers is plotted on the y-axis, along with the standard error for dark fixation condition (red circles), light fixation condition (blue circles), and for the original free looking paradigm (Experiment 1, black rhombi). Data points are rendered with three luminances, representing the three different reflectances of the target surface (e.g., dark red points represent the matches for the 35% reflectance target surface in the dark fixation condition). (B) Fixation effect as a function of the fixated luminance difference. The three gray and blue intensities represent the three reflectance values of the target surface and the different symbols represent the different conditions. The circles are gray when the fixated luminance difference is computed as the average over the time sequence and blue when the fixated luminance difference is computed as the last difference in the time sequence.

luminance difference between the fixated positions changes over time. When the fixation effect is expressed as a function of the average fixated luminance difference over time, the data points do not lie on the regression line, and the effect of fixation on the lightness matches is lower in the $L > D$ conditions than the $D > L$ conditions (Figure 7B, closed and open gray circles, respectively). If these effect sizes are expressed as a function of the luminance difference at the end of

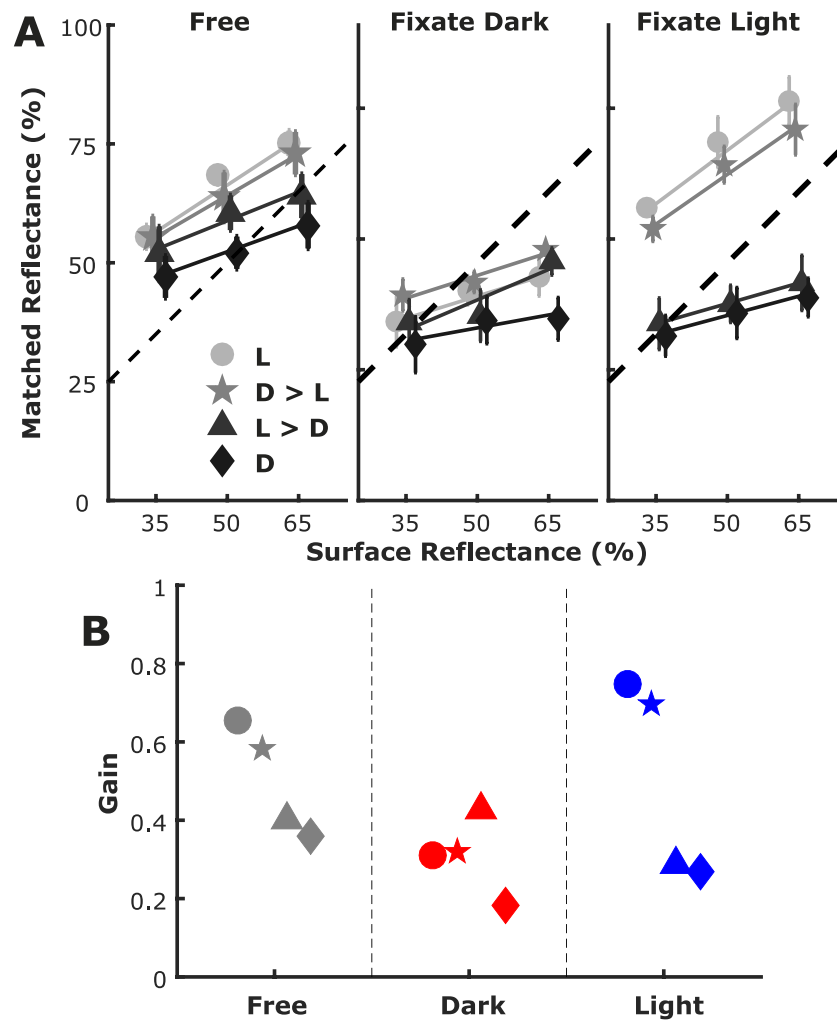


Figure 8. Lightness matches regressed as a function of surface reflectance. (A) Lightness matches averaged across observers, shown with the standard errors, for the four conditions for Experiments 1 and 2. The black dashed line represents the unity line. Continuous lines represent the regression lines for all the conditions separately. (B) The slopes of the regression lines on A are summarized for the free looking experiment (Experiment 1) and for the two fixation conditions, dark and light (Experiment 2).

the time sequence, then the points are closer to the predictions on the regression line (Figure 7B, closed and open blue circles), consistent with the finding that the last moments in the time sequence are more heavily weighted during the temporal integration of the luminance distributions (with the same regression line: $r^2 = 61\%$ and $r^2 = 83\%$, with the average fixated luminance difference and with the final fixated luminance difference, respectively).

Figure 8A shows the lightness matches regressed as a function of the surface reflectance, for the four conditions in Experiment 1 and in the dark fixation and light fixation conditions of Experiment 2. The regression slopes are a measure of perceived difference in reflectance: the higher the slope, the higher the difference in the perceived reflectance. In the free looking experiment (Experiment 1), there was a trend for the slopes in the conditions L and $D > L$, where the surface appears lighter, to be higher than the ones in

the D and $L > D$ conditions. This main effect of the dynamic condition did not quite reach significance, as shown by a repeated measures ANOVA, $F(3, 15) = 2.54$, $p = 0.096$. When the observers were forced to fixate a light point on the surface, the slopes for the conditions L and $D > L$ were significantly higher than for the condition D , $t(3) > 6.6$, $p < 0.01$. When forced to fixate a dark point on the surface, the slopes for all conditions were very similar and statistically indistinguishable. This result is supported by a repeated measures ANOVA (Fixation \times Condition) on the slopes from the forced fixation experiment (Experiment 2) that showed a significant interaction between Fixation and Condition, $F(2, 6) = 6.28$, $p < 0.05$.

To summarize, these results suggest that when the surface is more exposed to the light or when it stops in the lighter part of the scene, the differences in perceived reflectance are amplified (as assessed by the slopes in Figure 8A; see Figure 8B for a summary) in compar-

ison to when the surface was presented in dim light or it stopped there. This difference was clearly present when observers were required to fixate the lighter part of the surface, whereas it disappeared when they fixated the darker part. In the free looking paradigm, this difference seemed reduced compared to the case when observers were asked to fixate a light point on the surface. This is consistent with the fact that the fixations in the free looking paradigm had a tendency to be within lighter areas of the surface, but not as light as the extremes chosen for the forced fixation condition.

On a speculative level, this result could be seen as a trade-off between the need to perceive reflectance differences and to have a stable percept, despite changes in the illumination. In fact, Figure 8A suggests that when people are fixating a light point on the surface, their matches are more affected by the changes in illumination than in the other conditions (the distance between the data points in the $L > D$ conditions compared to the data points in the $D > L$ conditions is the highest in the light fixation case).

Experiment 3: Dynamics of lightness estimation

The results of Experiment 1 emphasized the importance of motion sequence time order: the matches were more influenced by the luminance distributions at the end of the sequence. In that experiment, observers were always shown the full sequence, therefore it was not possible to distinguish the contribution of the individual moments during the sequence. Furthermore, the observers knew that the whole sequence was to be presented; thus, they might have only paid attention at the end of the sequence, just before they provided their answer. In other words, the results could have been driven by the task. We therefore conducted another experiment in which the scene ceased at different time points in an unpredictable fashion. As a result, our observers had to pay attention to the whole sequence and we could observe the update of lightness matches as the sequence progressed in time.

Methods

In this experiment, we only showed moving conditions ($D > L$ and $L > D$) in the paradigm that were otherwise comparable to the other experiments in this study. Although we allowed our observers to freely view the scene, as in Experiment 1, we did not play the full 8 s sequence every time. The four sequence

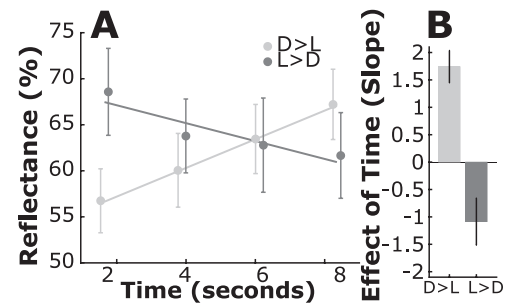


Figure 9. Lightness matches for different sequence durations. (A) Mean lightness matches and standard errors are represented on the y-axis for the two moving conditions, whereas the time point when the scene was ceased is represented on the x-axis. The continuous lines show the regression lines for the matches regressed as a function of the time point. (B) Effect of time on the lightness matches, expressed as the slope of the matches when regressed as a function of sequence duration. The analysis was done separately for every observer. The y-axis represents the average across observers for the two conditions (error bars denote the standard error).

durations (2, 3, 4, or 8 s) were randomized across trials, resulting in four timing conditions.

For each of the three reflectances, each of the two motion conditions and each of the four timing conditions, every observer produced five matches, giving 120 matches in total ($3 \times 2 \times 4 \times 5$).

Results and discussion

Figure 9 shows the lightness matches for the two moving conditions when the trials were stopped at different time points. The more the pendulum moved into a lighter illumination, the lighter the matches; the more it moved into a darker illumination, the darker the matches. This relationship was well described by a linear regression ($D > L$: $r^2 = 71 \pm 07\%$ and $L > D$: $r^2 = 65 \pm 15\%$).

In Experiment 1, we showed that observers could not discount the illumination (at least in our setup). In particular, we showed that the perceived lightness depends on the intensity of the illumination. This might suggest a constant update of a percept, with the object gradually becoming darker as it moves into shadow or lighter as it moves into a spotlight. In fact, statistical analysis confirms this explanation. We performed a three-way ANOVA using sequence duration (2, 4, 6, and 8 s), with moving conditions ($D > L$ and $L > D$) and surface reflectance as fixed factors. The ANOVA revealed an interaction between the moving condition and the sequence duration, $F(3, 15) = 7.552$, $p < 0.005$. The main effect of surface reflectance was significant, $F(2, 10) = 23.11$, $p < 0.0005$, whereas this factor did not significantly interact with any of the other factors, $F_s <$

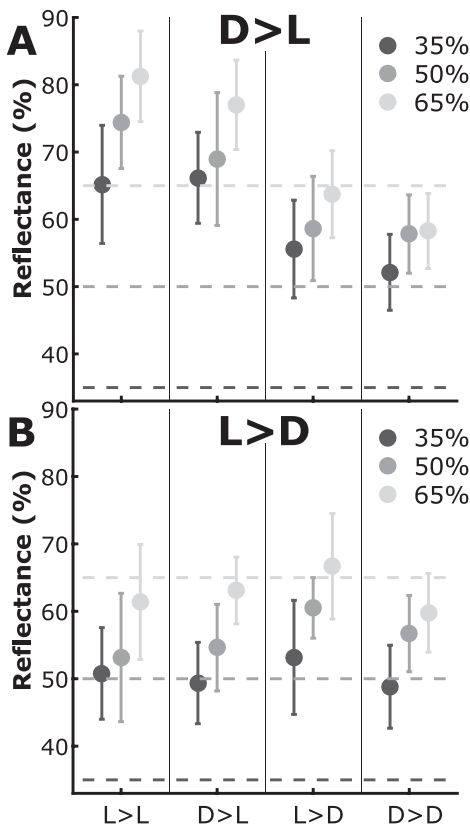


Figure 10. Lightness matches with a dynamic fixation point. The y-axis represents lightness matches averaged across observers (error bars denote standard errors). The dotted horizontal lines represent the three reflectance levels used for the targets. The x-axis stands for the four conditions of the fixation point. The two graphs show target motion, from dark-to-light (A) and light-to-dark (B).

.79, $p > 0.59$). In order to interpret the interaction between sequence duration and condition, we performed two separate linear regressions on the two conditions for every observer and analyzed the distribution of the slopes (average slope showed in Figure 9B). On average, the slopes for the $D > L$ condition are positive and for the $L > D$ condition the slopes are negative, both significantly different from zero according to one-tailed t tests: $L > D$, $t(5) = -2.55$, $p = 0.026$; $D > L$, $t(5) = 5.87$, $p = 0.001$.

These results strongly suggest that the lightness percept is constantly updated, matching the dynamic change of the luminance distribution. Considering the $D > L$ condition, the matches obtained after 6 s are lower in reflectance than those obtained after 8 s, when the pendulum reached the most illuminated part of the scene. Statistical analysis (after averaging over surface reflectance) also confirms that the lightness of the target is updated in the final 2 s: one-tailed t test, $t(5) = -2.0608$, $p < 0.05$. It is worth noting that in the $L > D$ condition, there is no significant difference between the matches obtained after 6 s and those obtained after 8 s.

However, the change in the average luminance of the surface between 6 and 8 s in the $L > D$ was about one order of magnitude smaller (approx. 1 cd/m^2) than in the $D > L$ condition. Hence, the lightness update in this last time point of the $L > D$ condition might be negligible. In fact, the differences in the matches over time are highly correlated with the differences in the average luminance of the surface ($r^2 = 58 \pm 15\%$ and $54 \pm 15\%$, for the $D > L$ and the $L > D$ conditions, respectively).

Given this finding, it is also important to query the time effects in the forced looking paradigm.

Experiment 4: Dynamic forced looking

By forcing the observers to keep fixating a certain point on the moving surface (in Experiment 2), we showed that the fixated position could influence the perceived lightness of the surface. It is reasonable to ask whether this effect is also time dependent (i.e., whether the fixation position has a constant impact on lightness in any time point or if it changes over time). For example, is there a higher impact in the final time points of the sequence? To address this issue we conducted an experiment in which we dynamically manipulated the fixated position by moving the fixation point across the surface.

Methods

We repeated Experiment 2 (forced looking) but only with the two moving conditions ($D > L$ and $L > D$). Also, the previously static fixation point was now moving from left to right across the target surface ($L > D$) or from right to left ($D > L$), along the horizontal axis of the ellipsoid. The new dynamic fixation point followed the trajectory between the two fixation points used in Experiment 2. The motion of the fixation point was synchronized with the motion of the target surface so then when the surface completed its motion cycle from one side of the scene to the other, the fixation point also completed its full path. There were also two conditions with static fixation, dark fixation ($D > D$) and light fixation ($L > L$), identical to the original fixation conditions in Experiment 2 (Figure 10).

For each of the three reflectance values, each of the two motion conditions and each of the four fixation conditions, every observer produced five matches, giving 120 matches in total ($3 \times 2 \times 4 \times 5$).

Results and discussion

The results are presented in Figure 10. We performed two separate two-way repeated measures ANOVAs for the two moving conditions of the surface motion ($D > L$ and $L > D$). In Experiment 2, in the $L > D$ condition there was no effect of the fixation position and similarly in this experiment, the ANOVA showed only a significant effect of surface reflectance, $F(2, 6) = 59.2$, $p < 0.001$.

In the $D > L$ motion condition, the ANOVA revealed a significant main effect of the reflectance, $F(2, 6) = 12$, $p < 0.01$, a significant main effect of the fixation condition, $F(3, 9) = 8.16$, $p < 0.01$, but no interaction, $F(6, 18) = .57$, $p = 0.749$. Thus, we could test our hypothesis after averaging over surface reflectance. Since the effect of fixated luminance was visible only in the $D > L$ condition, we restricted our further analysis to this case. Considering the conditions in which the fixation point was static ($D > D$ and $L > L$; Figure 10), a paired one-tailed t test showed that when observers were forced to fixate the light fixation point ($L > L$ fixation condition) they produced significantly lighter matches, $t(3) = 4.29$, $p < 0.05$, than when forced to fixate the dark fixation point ($D > D$ fixation condition). This result basically replicates what we found in Experiment 2. A further comparison showed that moving the point from the rightmost dark part of the surface into the light ($D > L$ fixation condition) caused the matches to be, on average, significantly higher than those obtained from the condition in which the fixation dot was always in the darker fixation position: one-tailed paired t test, $t(3) = 3.26$, $p < 0.05$. When the point was moved from the lightest fixation position into the darker ($L > D$ fixation condition), the lightness matches were, on average, lower than in the $L > L$ fixation condition: one-tailed paired t test, $t(3) = 2.56$, $p < 0.05$. This result shows that forcing the fixations to be on light areas at the beginning of the sequence and on dark areas at the end was enough to make the surface appear darker in comparison to the original light fixation condition. The same is true for the case in which the fixation dot moves into the lighter area of the surface: the surface appeared lighter than in the condition when the fixation dot was on the darkest region of the surface. These results now reveal that the effect of the fixation position is more prominent at the end of the motion sequence.

General discussion

This study presents four experiments inspired by the idea that shadowed regions in the scene systematically influence eye movements. Our previous research

demonstrated this tendency using different methodologies and experimental settings. Eye tracking studies showed that observers, when providing a lightness match of a shaded object, tend to spend more time gazing at the more intensely illuminated parts of the object (Toscani et al., 2013a, 2015). Further results showed that observers consistently change their lightness judgment (Zdravković et al., 2006) when the size and location of cast shadows are manipulated.

In the present study, we explored the temporal effects of the measured change in lightness. Classical findings on the interrelation of reflectance and illumination maintain that objects look darker in the shadow and lighter in the spotlight (Katz, 1935). It has been shown that, to some extent, observers can disentangle surface reflectance and illumination (for review, see for example Maloney, Gerhard, Boyaci, & Doerschner, 2011) and can even partially compensate for illumination variation across space (Gilchrist, 1977, 1980; Kardos, 1934). Our present attempt to include temporal effects added two novel features to existing paradigms. Similar to the previous research, we created a scene with a variable illumination (i.e., a light field), but we included temporal variations of the illumination on the object by moving our target through the light field. This target motion enabled us to measure the lightness status between the two extremes, the spotlight and the shadow region.

The degree of lightness constancy achieved in our study was far from perfect, even though observers could see the target object moving through an illumination gradient. The lack of perfect lightness constancy is a common pattern of results in lightness perception studies, both with real and artificial stimuli. For instance, in the study by Ripamonti et al. (2004) observers were asked to judge the lightness of a card presented with different vertical orientations. Their lightness matches were strongly affected by the illumination conditions (i.e., card orientation) and constancy ranged between 17% and 63%. Snyder, Doerschner, and Maloney (2005) provided their observers with realistic illumination cues (i.e., glossy spheres), showing that these cues improved lightness constancy, which ranged from 19% to 85%. Even in nearly natural laboratory experiments (e.g., Gilchrist et al., 1999) lightness constancy was not perfect. Lightness constancy ranged around 50% in our experiments (see Figure 3), which is in a good agreement with these earlier studies. It is also an ideal situation to study constancy mechanisms, which are engaged but do not perform perfectly (i.e., performance is far from floor and ceiling). Moreover, our experimental task was designed to elicit lightness judgments in our observers (see Toscani et al., 2013a). Our data indeed show that observers did not base their judgment purely on the luminance of the target surface (e.g., on the mean

luminance distribution), because the luminance values of the chosen paper chips were more than twice as intense as the luminance values of the target surface (see Figure 1 for the conversion of matched reflectance into luminance).

The differences between the matches on the dark side and on the light side of our display could be partly due to simultaneous contrast effects. Mostly, the luminance ranges of targets and backgrounds are overlapping, but in particular for the high target reflectance the target is brighter than the rest of the scene on the light side. If simultaneous contrast effects were dominating, we would expect all three target reflectances on the light side to appear equally white, as shown by Economou, Zdravkovic, and Gilchrist (2007, see figure 8). Our articulation of the scene, with multiple objects and illumination levels, preserves the natural appearance and the three target reflectances produced three very different results. Therefore, we think that the potential contribution of simultaneous contrast is small. Furthermore, it would not invalidate our conclusions about the dynamic cases. It is these differences in the matches between the experimental conditions that allow us to draw our conclusions about the role of eye movements and about the dynamics of lightness perception.

Lightness updating

We found that observers are sensitive to the temporal order of events in the light field. The lightness judgment differs if the target travels into a shadow versus into a spotlight. We also tested whether eye movements play a role in this very specific type of constancy failure. The fixation effect for the target terminating its motion on the bright side ($D > L$) was higher than for the opposite trajectory ($L > D$), as demonstrated by the significant interaction between the fixation condition (light fixation and dark fixation) and surface moving condition ($L > D$ and $D > L$).

This result is consistent with findings from Experiment 4, in which we scrutinized the location in the scene where gaze landed and compared the luminance profile with lightness matches. The motion of the fixation dot during the time sequence shifted the matching results toward the dark fixation condition in the case in which the dot was moving from light to dark, and toward the light fixation condition in which the dot was moving from dark to light. In fact, when the effects of fixation position (Light Fixation matches – Dark Fixation matches in Experiment 2) are expressed as a function of the luminance difference at the end of the time sequence, then the points are closer to the predictions from the regression analysis on the stationary conditions data (Figure 7B: closed and opened blue circles).

These results also support the idea that the effect of fixation position on lightness matches, previously reported for stationary surfaces (Toscani et al., 2013a, 2013b, 2015), is modulated over time. In Experiment 1, within the free looking condition, observers focused their fixations on higher values of the target's luminance distributions. However, they did not focus on the maximum, which can be easily seen when Figures 2 and 6 are compared. Figure 8, containing the results from the forced fixation experiment (Experiment 2) offers an explanation for this strategy. Fixation on the luminance distribution maximum (i.e., the brightest pixel on the surface) leads to a higher dependence on the illumination and consequently leads the percept away from constancy.

In general, the luminance profile is a product of the reflectance and illumination distributions. When one of the two is homogeneous, the change in the luminance profile is exclusively dictated by the other, nonhomogeneous factor. In our case, this is the illumination. Since lightness constancy is defined as a perfect correspondence between reflectance and percept, constancy gets worse when focusing on luminance maxima due to variable illumination. This would amplify the perception of nonexistent reflectance differences. Such a scenario can be observed in Figure 8A, which shows exaggerated differences between the matches when observers are forced to fixate the particularly bright point on the left side. In the free looking paradigm, observers seem to naturally choose a better strategy. They tend to fixate regions brighter than the median luminance values, but not the illumination maxima. This maximizes the effect of reflectance in the luminance distribution and takes advantage of better visibility provided by more illumination. However, at the moment this is only our speculation.

This leads to the most intriguing outcome of this study. In Experiment 3, we had observers provide lightness matches at different times during the target's trajectory through the light field. We discovered that the reported lightness increased and decreased along with the change in illumination level. This shows that if we take a target from spotlight to shadow, observers update its appearance along the way through the illumination gradient. This experiment reveals the time course of the lightness constancy and its failure (Figure 9A).

Our results suggest that lightness is updated continuously. In fact, in the case of a trajectory toward the bright part of the scene, there is a significant update in the target lightness between the penultimate and ultimate points of measurement (i.e., at 6 and 8 s). This change in percept reflects the physical conditions; that is, there was a significant increase in the illumination (an increase of approx. 10 cd/m^2 for the average luminance of the target surface).

We are positive that this updating process is driven by the change in the luminance distribution, which in return is a result of the change in the illumination. That is, we can only measure a change in lightness when there is a sufficient illumination change. Consequently, when the target traveled to the dim portion of the scene, there was no significant difference in the lightness matches.

In order to estimate the invariant property of the object (reflectance, in this case), observers should not completely rely on the luminance distribution, which would produce mere brightness matches. In other words, observers tend to avoid the dim parts of the scene and the dim parts of the object and they also do not fixate the misrepresentative luminance maxima. In our previous research, we also found that this tendency to avoid shadows does not always simply reveal low-level mechanisms that register low-contrast–uninformative areas, driving an individual to avoid them altogether. For instance, we used perceptual and cognitive tasks with faces partially covered in shadows to learn that the typical pattern of eye movements for faces is not altered in the shadow region; observers simply fixate less in these regions (Hermens & Zdravković, 2015). It suggests that they know that they are looking at the face but just prefer to sample information from a region of better visibility.

Integration of serially sampled information

In our experiments, the surface reflectance does not change during the target motion, therefore the time sequence could be seen as a series of successive samples provided to the visual system to achieve an estimate of a constant magnitude (i.e., the surface reflectance). Integration of serial samples on a constant property has been studied in the visual domain (Juni, Gureckis, & Maloney, 2012; Parker, Lishman, & Hughes, 1992; Werner, 2007) and the haptic domain (Lezkan & Drewing, 2014). These studies show that the temporal order in a serial stimulation plays an important role in perception. Parker et al. (1992) presented a series of images filtered at different spatial frequencies, shown in a coarse-to-fine and in a fine-to-coarse order. Observers had to rate the quality of the image after the sequential presentation. When the order was from coarse-to-fine, the perceived quality of the image was judged as higher. Juni et al. (2012) required their observers to estimate the position of a hidden visual target after being exposed to seven sequential cues to the target location, sampled from seven Gaussian populations, centered on the target but each with a different variance. At the end of every trial observers were provided with visual feedback indicating the target location. In one condition, the variance was decreasing throughout the

sequence and in the other, it was increasing. Observers adapted their strategies and gave more weight to more precise cues and less weight to less precise cues, irrespective of the sequence. In our present experiments, only the temporal order was crucial and no adaptive behavior or preference was found.

Differently from our experiments, in both the Juni et al. (2012) and Parker et al. (1992) studies, observers were presented with multiple targets that they were required to integrate; that is, the identity of the targets as a single object was not made explicit. Lezkan and Drewing (2014) asked their participants to make haptic judgments of the spatial frequency for a virtual texture after multiple explorations of that texture. They manipulated the spatial frequency of the texture during the trial in order to measure the importance and contribution of each individual sequential movement. Similar to our results, the movement temporally closer to the comparison had a greater impact on percept. This result, just like in our case, came from a study in which the target had an explicit identity that did not change across time. Lezkan and Drewing (2014) explain their data in terms of memory decay, arguing that memory limitations might lead to decreasing weights for the memorized information with an increase in the temporal distance to the comparison stimulus.

This, however, was not our experience with memory matches. When observers were exposed to an object oscillating a few times between the regions of high and low illumination and then asked observers to make a memory lightness match only after we removed this object from the view, they showed a strong preference toward the appearance in spotlight (Zdravković, 2008). In this case, memory matches did not depend on the last experienced illumination.

Olkkonen and Allred (2014) demonstrated that memory interacts with color constancy. The shift in perceived hue of a target expected with certain contextual conditions is weakened by a short retention interval between the visual stimulation and the behavioral response. However, note that our paradigm did not include any significant retention interval. Furthermore, according to Olkkonen and Allred's (2014) results memory might increase the dependency of lightness on the illumination, but this cannot explain the time order effects we observed.

Memory effects in relation to temporal order were also studied in cognitive psychology. According to the serial position effect (Ebbinghaus, 1913; Murdock, 1962), the first and the last items in a series are the most accessible. Therefore, if memory was the only important factor, it would be reasonable to expect that the time points in the sequence are integrated by weighting the well-remembered items the most. Therefore, the first and the last moment should have a special impact, irrespective of the time chosen for the response.

In fact, this has been reported recently in the case of object size and location, motion direction, and facial expression (Hubert-Wallander & Boynton, 2015). A clear order effect was shown, and some visual features were found more influenced by earlier items (location) whereas some by later (size, motion, expressions). An update of one's percept for visual features changing over time has been reported even in the case of lightness illusions (Annan & Gilchrist, 2004). In these experiments, the lightness change was driven by the change of surfaces in the scene and the initial moments carried more weight.

In a previous study, Werner (2007) found increased levels of color constancy when a target object moved across a background. This seems to be at odds with our results. However, in the study by Werner (2007), the illumination changed from scene to scene and the observers had an assigned time to adapt to this overall illumination change (15 + 5 s). In such conditions, as the target moved against the homogeneously textured background, more information could be gained by comparing the target to the different parts of the background. In our study, the background wall was homogeneous in reflectance but there was an overall light gradient, through which target moved within 8 s. This difference in procedure (and no adaptation) would lead to less lightness constancy, as we observed.

“What you see is what you need”

Another possible explanation offered in literature is that “what you see is what you need” (Triesch, Ballard, Hayhoe, & Sullivan, 2003). Specifically, it has been proposed that the information useful for a task is sampled “just in time” (Ballard, Hayhoe, & Pelz, 1995). In other words, it has been proposed that the visual system accesses the visual scene in an online fashion, rather than performing a parsimonious sampling of the visual scene that, for further processing, must depend on visual memory (Rensink, 2000). For instance, when observers had to copy an arrangement of blocks, they repeatedly shifted their gaze to the blocks which are task relevant, rather than storing the arrangement in the visual memory (Ballard et al., 1992; Ballard et al., 1995). This view implies that instead of storing all the sampled information and only relying on (short term) visual memory, the visual system also uses the scene itself as memory storage. Information is only retrieved from this storage when it becomes relevant for the current task. Our methodology forced participants to keep the information in the internal storage, until they were able to approach the lightness scale. Still, they were continuously updating the information, following the change in illumination conditions. However, it should be noted that the change we presented them with was very systematic and expected based on the

normal visual experience with objects travelling through light fields. Finally, we demonstrated that not all the information is given the same weight, and the system preferentially uses the currently available luminance distribution, updating the percept to suit current physical conditions in the visual scene.

Conclusions

Our experiments demonstrated that participants tend to fixate a bright region even when the scene is complex and articulated, and even when it is dynamic. We confirmed that lightness perception is affected by all the things we varied in the experiment: reflectance, illumination level, and fixation pattern. Our methodology enabled us to measure the contribution of each of these factors, as well as the time course of their impact.

Our results demonstrate the importance of where in the scene an observer fixates. This has a significant effect on lightness perception. The fixation strategy that observers naturally choose does optimize the extraction of information about lightness from the luminance distribution. Observers are focusing on the part of the object that is most informative about an important object property; that is, the reflectance.

Keywords: eye movements, lightness, light field, lightness constancy, surface albedo

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