Reflectance identification of patterned 3-D real objects

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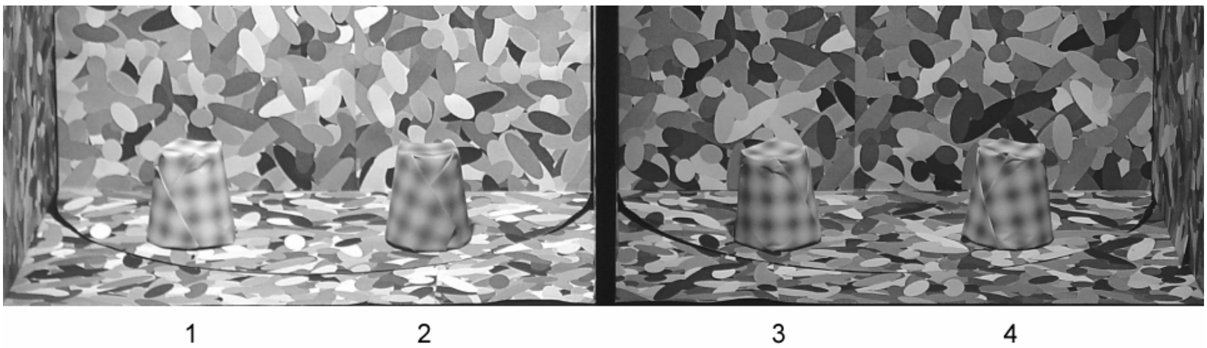
ABSTRACT
We show empirically and computationally that observers identify patterned achromatic objects across illumination conditions by using perceived brightness and contrast, rather than by a process of reverse optics.

1. INTRODUCTION

The reflectance of a material is an invariant that could aid in identification across viewing conditions[1-4]. To estimate reflectance, the visual system has to account for variations in illumination. Studies have shown that material matches across illuminants cannot be explained exactly by reflectance or luminance matching[5-10]. This study examines the percepts that underlie material identification across illumination conditions.

Studies of lightness perception have almost exclusively used plain stimuli. Many objects in the world are patterned, and there are reasons to expect material identification to be better for patterned than for plain objects: (i) change in illuminant energy changes surface luminance, but leaves surface pattern contrast relatively unchanged, (ii) in identifying a material, observers can use reflectance extremes or reflectance range to supplement mean-reflectance, (iii) memory for contrast is substantially better than memory for grey levels[11].

Consider Figure 1. The stimuli consist of crumpled papers with plaid patterns. The compartments are illuminated by separate light sources differing four-fold in intensity. Three of the objects are made from the same paper and one from a different paper. Which is the odd object? To perform this task correctly, first you have to choose the side that contains the pair of dissimilar objects. Then you have to identify which of those two objects are different from the pair under the other illuminant. For comparison under a single illuminant, Figure 2 shows objects 3 and 4 moved behind objects 1 and 2. It is clear that object 2 has a lower mean-reflectance than the other three. Which is the odd object in Figure 3? Figure 4 shows all the objects under a single illuminant. It is clear that object 3 has a lower reflectance-contrast than the other three. We are interested in identifying the percept that underlies both correct and incorrect identification in these two cases.



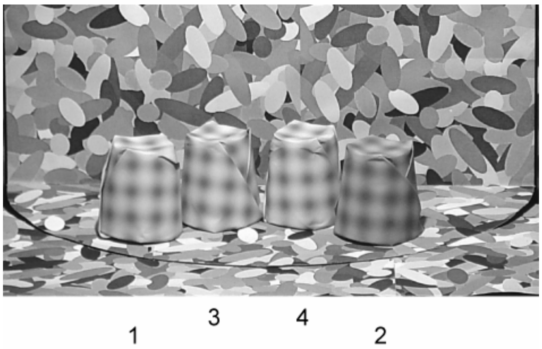


Figure 1: Photograph of stimuli under experimental presentation. The two compartments each contain a pair of objects illuminated independently by light sources that differ by a factor of four. All four objects have the same reflectance-contrast, but differ in mean-reflectance.

Figure 2: Photograph of stimuli placed in a single compartment for comparison purposes. When all four objects are under the same illuminant, it is clear that object 2 has al lower mean-reflectance.

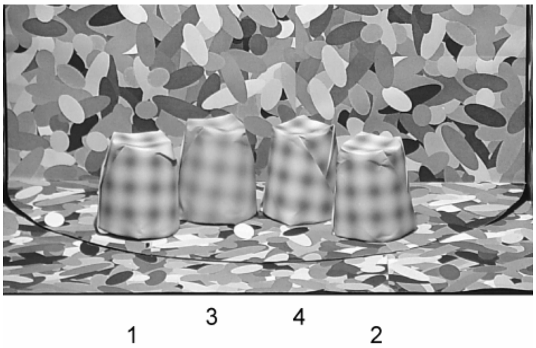


Figure 3: Photograph of stimuli under experimental presentation. The two compartments each contain a pair of objects illuminated independently by light sources that differ by a factor of four. All four objects have the same mean-reflectance, but one differs in reflectance-contrast.

Figure 4: Photograph of stimuli placed in a single compartment for comparison purposes. When all four objects are under the same illuminant, it is clear that object 3 is lower in reflectance-contrast.

2. METHODS

We used this apparatus to run three experiments under free binocular viewing, using a method of constant stimuli. In Experiment 1, observers were instructed to identify the object that was physically different from the other three. Test objects varied in mean-reflectance (Experiment 1a) or reflectance-contrast (Experiment 1b). Conditions were randomly interleaved within each session. Experiment 2 and 3 were run with the same observers using the same stimuli under identical viewing conditions. The only difference was in the instructions. In Experiment 2, test objects varied only in mean-reflectance, and observers were instructed to choose the object most different in brightness. In Experiment 3, test objects varied only in reflectance-contrast, and observers were instructed to choose the object most different in contrast.

Achromatic plaid patterns were computer generated by summing two identical sinusoidal gratings with orthogonal orientations and printed on paper. The mean-reflectance and reflectance-contrast were precisely callibrated. Papers were crumpled around inverted cups and presented in the manner shown above.

3. RESULTS

The proportions of side correct as a function of Δ mean-reflectance (or Δ reflectance-contrast) give a psychometric function for brightness (or contrast) discrimination. The proportions of object correct give a psychometric function for material identification. The results can be plotted like Figures 5 and 6. The 2AFC discrimination curves are symmetric (dashed curves). The 4AFC identification curves can be asymmetric depending on the underlying mechanism (solid curves). For each vertical pair of subplots, the top row indicates the test objects are under full illumination, while the bottom row indicates the test objects are under reduced illumination.

The identification curves in Figure 5 are based on observers using perceived brightness to pick the odd object when test objects varied in mean-reflectance. The brightness of a stimulus is equal to the mean luminance of the stimulus multiplied by an adaptive gain whose value is a monotonically decreasing function of mean luminance, $g = \kappa / (\kappa+L)$. Responses depend on the function defined by κ. ($\kappa=inf$) represents no adaptation, so brightness dissimilarities are based on mean-luminance. ($\kappa=0$) represents complete adaptation, so that identical materials appear identical across illuminants. The two middle pairs show simulations for moderate adaptation. The empirical results were asymmetric in the same manner as the two middle panels. This suggests that observers use perceived brightness to identify mean-reflectance across illuminants.

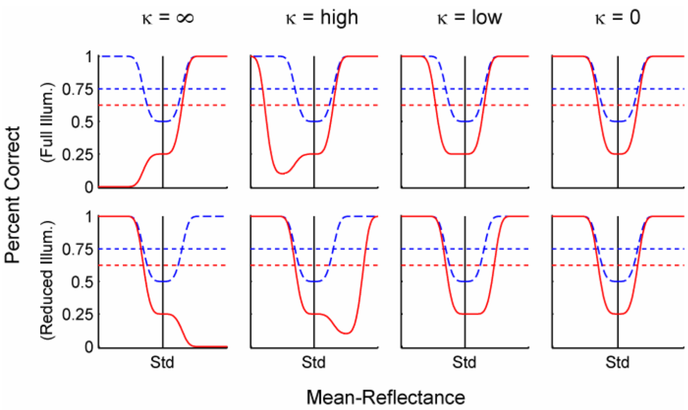


Figure 5: Hypothetical material identification functions based on brightness similarity.

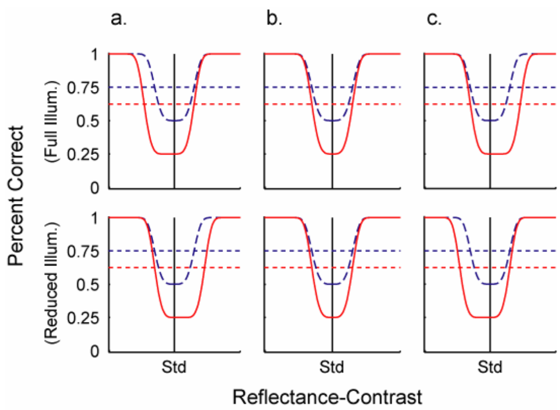
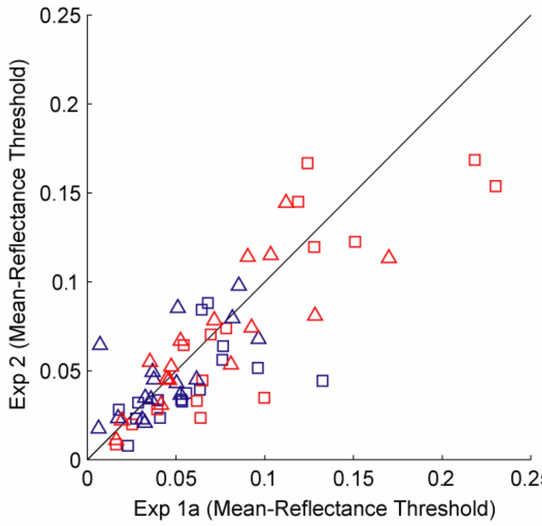


Figure 6: Hypothetical material identification functions based on perceived contrast.

Figure 6 shows three hypothetical responses to the identification task with tests varying in reflectance-contrast. All three models assume that observers use perceived contrast to pick the odd material. The left panel simulates the asymmetry in identification curves if perceived contrast increases with mean luminance[12]. The center panel is based on perceived-contrast being invariant to illuminant energy. The model in the right panel assumes that light reflected from the surface of an object acts as veiling glare to reduce the perceived contrast. The right panel is most similar to the actual results. This suggests that observers use perceived contrast to identify objects.

In Experiment 2, observers were instructed to choose the object most different in brightness while test objects varied in mean-reflectance. In Figure 7, identification thresholds of Experiment 1a are plotted against corresponding thresholds from Experiment 2. Most points fall close to the unit diagonal, indicating equal thresholds.

In Experiment 3, observers were instructed to choose the object most different in contrast while test objects varied in reflectance-contrast. In Figure 8, identification thresholds from Experiment 1b are plotted against the corresponding thresholds from Experiment 3. Most points fall close to the unit diagonal, indicating equal thresholds.



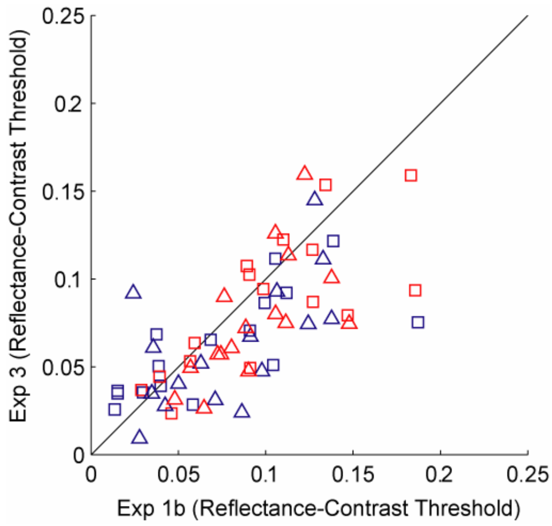


Figure 7: Mean-reflectance thresholds for side-correct and object-correct functions from Experiment 1a versus Experiment 2.

Figure 8: Reflectance-contrast thresholds for side-correct and object-correct functions from Experiment 1b versus Experiment 2.

4. CONCLUSIONS

Separating material properties from illumination variations is an important visual task for functioning in the real world. If flat grey papers are present on identical backgrounds under different levels of illumination, reflectance-ratios can be approximated well by luminance-ratios (object:background), which in turn are independent of illumination level. It is not surprising that lightness constancy holds in such conditions[1, 13]. If one of the papers is slanted towards the observer, its luminance (and luminance-ratio) will be affected by the slant. Reflectance-ratios could still be approximated by luminance-ratios if the angle of orientation of each paper to the illuminant is estimated correctly. Observers vary considerably in lightness estimates, i.e. in controlling for slant[6, 14, 15]. For 3-D grey objects, the estimations are further complicated by the presence of multiple facets, highlights, and shadows. This study shows that the presence of internal pattern helps to ameliorate some of these difficulties. First, pattern contrast is relatively immune to illumination and viewing conditions. Second, observers can use contrast-memory across space and time.

In the achromatic domain, the simplest percepts are perceived brightness and perceived contrast. Two types of evidence show that these percepts are used in identification of patterned 3-D objects across illumination conditions. First. identification results can be simulated by models that perform identification on the basis of brightness or contrast dissimilarity. Second, identification thresholds can be predicted from observers' judgments of brightness or contrast dissimilarity. These analyses argue against a reverse optics model of lightness perception, where observers first estimate illuminant intensity and then extract relative lightness by discounting the illuminant.

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