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Preconstancy Information Can Influence Visual Search: The Case of Lightness Constancy

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Can visual search be based on preconstancy representations of the scene—that is, ones in which accidental characteristics of the scene, such as shadows, point of view, and distance, have not yet been discounted? This question was addressed within the specific context of *lightness constancy*, the phenomenon that surface lightness is perceived as relatively unchanged despite changes in illumination conditions. Three experiments yielded evidence of preconstancy influence on visual search. This was true even when the preconstancy information that seemed to influence search was unavailable at a reportable level. The results suggest that visual search processes can be engaged before the processing that leads to the experienced perception of the scene is complete.

Being able to search one's environment from a distance is almost certainly one purpose for which visual systems evolved. A question that arises, given that the environment is being searched from a distance, is what the nature of the representation is through which search occurs. As visual information is processed, it is transformed from relatively raw representations (e.g., luminance values registered at the level of the photoreceptors) to relatively interpreted representations (e.g., lilies, sunflowers, and weeds in a summer garden). At what point or points throughout this transformation process are visual search mechanisms engaged? This question was addressed in the present study within the context of lightness constancy.

The perceptual constancies are a class of phenomena according to which the visual system discounts accidental characteristics of the scene such as shadows, point of view, and distance and comes to represent the world in a relatively veridical manner. *Lightness constancy*, in particular, refers to the fact that the surface reflectance of objects is perceived as relatively constant despite spurious differences in the scene, like illumination or transparency changes. Cast shadows, sunbeams, and darkened glass are a few examples of such spurious characteristics. We do not, for example, perceive a region of the sidewalk that is in the shadow of a tree as being made of a darker shade of concrete (i.e., one that reflects less light) than the rest of the sidewalk. Instead, the perceptual system seems to take into account not only the amount of light that is being reflected from the various patches of sidewalk (*luminance*) but also the amount of light that is shining on those various patches (*illumination*). The sidewalk, then, is perceived as consisting of a relatively constant shade of gray concrete (*lightness*).[1]

Lightness constancy is a form of constancy that we thought should be especially relevant for visual search. Natural scenes are fraught with changes in illumination that are spurious in the sense that they do not reflect boundaries of meaningful objects or regions in the scene. As an illustration of this point, imagine a forest on a sunny day. On the one hand, an animal that is consistently duped into thinking that the many shadows and other lighting changes in its world represent actual changes in surface color would be inefficient at searching its environment. One might hypothesize, therefore, that visual search through a scene would be based on a representation that has already been resolved for spurious changes in illumination, a representation that we will refer to as *postconstancy*. On the other hand, constancy resolution requires time, and visual search often requires immediacy. Therefore, one might hypothesize that search processes would be engaged even before constancy resolution is complete and therefore would be based, at least initially, on a representation that has not yet been resolved for spurious changes in illumination, a representation that we will refer to as *preconstancy*.[2]

Previous studies indicate that at least some of the information that would be necessary for constancy resolution is available sufficiently early for visual search processes to be based on post-

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[1] We are using the conventional terminology of *lightness* to refer to perceived reflectance, where reflectance is the proportion of light that a surface reflects relative to that which an ideally reflecting surface would. *Brightness*, in contrast, refers to perceived luminance, where luminance is the absolute amount of light reflected from the surface.

[2] Ultimately, it is inappropriate to conceptualize constancy processes as dichotomous. Throughout this paper, we use the terms *preconstancy* and *postconstancy* heuristically as a means of separating the most developed representation of the scene in terms of surface lightnesses (postconstancy) with incompletely developed representations of the scene in terms of surface lightnesses (preconstancy).

constancy representations. Rensink and Cavanagh (1993, 1998; see also Elder, Trithart, Pintilie, & MacLean, 1998), for example, showed that shadow regions are represented and discounted as shadows, rather than as something else (e.g., object contours), sufficiently early that search for a target that is defined by orientation is uninfluenced by them. That is, as far as the visual-search task was concerned, the shadows were effectively not part of the scene. Lightness constancy depends on shadows being perceptually categorized as such (e.g., Gilchrist, Delman, & Jacobson, 1983). Therefore, the fact that shadows were categorized early indicates that at least some of the necessary conditions for search to be based on a postconstancy representation are met.

Watanabe and Cavanagh (1992, 1993) made a related point. They noted that a given location can project only a single luminance value to a corresponding point on the retina. When a transparent surface is superimposed on another surface, however, qualities of those surfaces support the perceptual experience of superimposed layers. Watanabe and Cavanagh were able to demonstrate that this "phenomenal scission" process (e.g., Anderson, 1997) occurs fairly early within the stream of visual processing, specifically, within about 60 ms of stimulus presentation. Thus again, to the extent that lightness constancy depends on the organization of regions into different transparent surfaces, when such are present in the scene, Watanabe and Cavanagh's results indicate that at least some of the necessary conditions for search to be based on a postconstancy representation are met.

Finally, and more generally, many studies have shown that visual search is based on properties of the scene, rather than on properties of the retinal image. To the extent that constancy resolution is part of scene representation, these results suggest the possibility that search may be based entirely on postconstancy representations. Enns and Rensink (1991), for example, showed that search can be based on the three-dimensional properties that are depicted in two-dimensional line drawings (see also Humphreys, Keulers, & Donnelly, 1994). Relatedly, it has also been shown that shape-from-shading properties of displays can drive search performance (Aks & Enns, 1992; Enns & Rensink, 1990a, 1990b; Kleffner & Ramachandran, 1992; Ramachandran, 1988). He and Nakayama (1992) showed that search can be based on perceptually completed representations of stimuli behind occluding regions (see also Rensink & Enns, 1998), and Davis and Driver (1994, 1997) showed the same for the illusory surfaces that are perceived in Kanisza triangle-type stimuli (see also Rubin, Bauer, & Reitzen, 1999; Shomstein & Rubin, 1998). Finally, and most directly relevant to the current question about lightness constancy, Aks and Enns (1996) have shown that size constancy can influence visual search.

Although all of these results suggest that visual search can be based at least in part on postconstancy representations of the scene, they do not rule out the influence of preconstancy information. As mentioned earlier, it is possible that search processes can be engaged early, even before constancy resolution is complete, and that later, as the representation develops, they can be based on postconstancy information. In the series of experiments reported here, we addressed the following question: Does preconstancy information influence visual search? If so, it would indicate that search processes can be engaged before constancy resolution.

Experiment 1

In Experiment 1, participants searched for either of two targets, a dark-gray or light-gray square, among medium-gray distractors. One of the two targets was present on half of the trials, and neither was present on the other half of the trials. Under standard conditions, this would be an easy and efficient search task. That is, response time (RT) would be nearly invariant as a function of the number of items in the display (*set size*). In this study, however, a transparent filter was rendered over part of each search display, such that half of the items fell inside the filtered region, and half fell outside the filtered region (see Figure 1). This region simulated a 50% filter, such that any stimulus that fell within it was reduced in luminance by 50% relative to when it was outside of the region. In addition, the filter was made to appear as if it were floating out in front of the search display by using binocular-disparity cues. This apparent depth created a strong impression of looking through a transparent surface to the search surface behind. This is a situation in which, given lightness constancy, changes in luminance across the filtered and unfiltered regions should be discounted as due to the filter, rather than to changes in surface lightness.

To get at the question of whether visual search is ever based on preconstancy representations of the scene, we set up conditions in which the preconstancy information in the display was ambiguous with regard to whether the target was present or not, but the postconstancy information was unambiguous. These conditions were compared with ones in which both preconstancy and postconstancy information was unambiguous. To the extent that visual search is based on preconstancy representations, we expected the conditions with ambiguous preconstancy information to yield poorer performance than the conditions in which the information was unambiguous at all levels. To the extent that visual search is based entirely on postconstancy representations, however, we expected no particular difference between conditions because the postconstancy information was unambiguous in all cases.

To be specific, consider first the trials in which the dark target was present (see Figures 1A and 1B). Stimulus luminances were chosen such that when the dark target was outside of the filtered region (Figure 1A), it had the same luminance as the distractors that were inside the filtered region. (We refer to trials of this type as *luminance matched.*) Because both targets and distractors could be of that particular luminance, the preconstancy representations of luminance-matched displays were relatively ambiguous with regard to whether the target was present or not. When the dark target was inside of the filtered region (Figure 1B), however, its luminance matched that of none of the distractors. (We will refer to trials of this type as *luminance unmatched.*) These displays were unambiguous with regard to target presence both at preconstancy and postconstancy levels of representation. Analogous luminance-matched and luminance-unmatched conditions were established for the light target (see Figures 1C and 1D). In this case, the luminance-matched condition was when the light target was *inside* of the filtered region (Figure 1D); here, it had the same luminance as the distractors that were outside the filtered region. When the light target was outside the filtered region (Figure 1C), its luminance matched none of the distractors.

One of the purposes of including both the light and dark targets is that opposite predictions could be made with regard to display

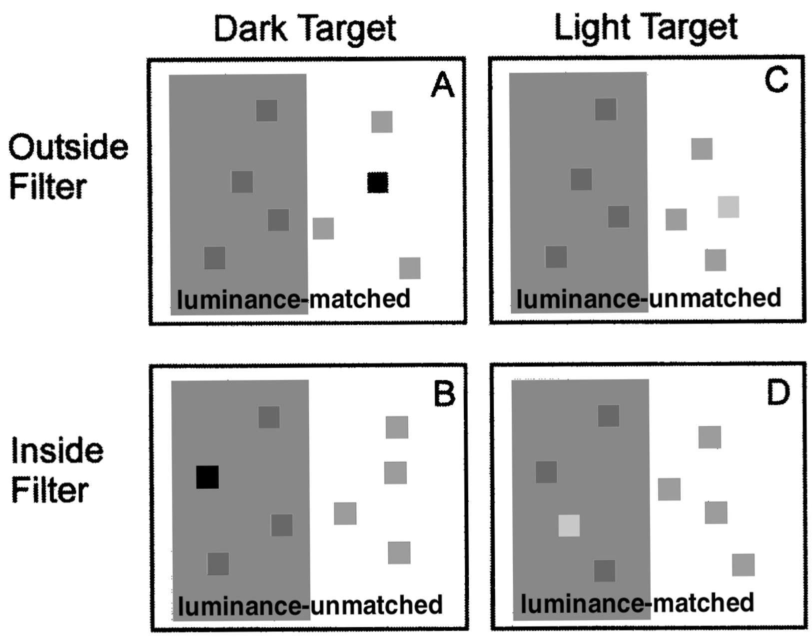

Figure 1. Sample target-present displays from Experiment 1. The darkened rectangle was presented in depth out in front of the rest of the display and simulated a 50% transparent filter. A: *Dark target outside the filtered region.* The luminance of the target matched the luminance of the distractors inside the filtered region. B: *Dark target inside the filtered region.* The luminance of the target matched no other stimulus. C: *Light target outside the filtered region.* The luminance of the target matched no other stimulus. D: *Light target inside the filtered region.* The luminance of the target matched the luminance of the distractors outside the filtered region.

region (filtered vs. unfiltered) for the two target types. The specific predictions were as follows: If visual search is influenced by preconstancy information, then performance should be worse for the luminance-matched, target-present trials (Figures 1A and 1D) than for the luminance-unmatched, target-present trials (Figures 1B and 1C). If, however, visual search is based entirely on post-constancy information, then there is no reason to expect performance to vary across the different types of target-present trials.

In visual search, performance can be worse in at least three different (nonexclusive) ways. Search can be slower overall. The slope of the function relating RT to set size can be steeper, indicating that more time was required per item. Or, finally, search can be less accurate. The logic laid out here is mute with regard to how search should be worse in the luminance-matched conditions, given preconstancy influence. The specific prediction depends on how the ambiguity in the luminance-matched conditions is resolved. This issue is discussed in more depth later in the paper.

Method

Participants. Twenty participants from the Pennsylvania State University participant pool were tested in Experiment 1. The participants were approximately 18–27 years of age. All reported normal or corrected-to-normal visual acuity and color vision, and all were naive as to the purpose of the experiment before being tested. They participated for extra credit in an introductory course in psychology.

Apparatus. Stimuli were presented on a 21-inch (53.3 cm) Nanao Flexscan F2-21 EX color monitor that was driven by a Number 9 Verge 3D graphics card. Trial events and data collection were controlled by an IBM-compatible, Pentium-based personal computer. A Stereographics CrystalEyes II stereo-display system was used to simulate depth through binocular disparity. This system presented separate left- and right-eye images using a set of liquid-crystal shutter glasses that were synchronized with the monitor. The presentation rate was 60 Hz per eye.

Task. The task was to search for a dark-gray or light-gray square among medium-gray distractors. Participants responded by pressing their left and right forefingers on the *z* and / keys of the keyboard, respectively. They responded with the dominant hand if either target was present and with the nondominant hand if neither was present. They were asked to make their responses as quickly as possible while maintaining 95% accuracy or better.

Stimuli. Participants viewed displays from a distance of approximately 60 cm while wearing the CrystalEyes glasses. A large (16.7° × 20.0° of visual angle), light-gray (luminance of 8.8 cd/m^2) rectangle was presented on the dark background of the monitor, in depth beyond the horopter. Search arrays were superimposed on this rectangle (presented at the same depth), and a 15.7° × 7.8° of visual angle, gray (4.33 cd/m^2), rectangular region that simulated a 50% filter was presented in depth out in front of part of the display. The filter surface appeared either over the left half or over the right half of the search surface. It was positioned 2.2° of visual angle in from the left or right edge, respectively, of the search surface and 0.7° of visual angle down from the top edge.

Depth was created by presenting separate left- and right-eye images of the various parts of the display (see Figure 2 for an illustration). The right-eye image of the filter surface was 0.30° of visual angle to the left of the left-eye image (crossed disparity), resulting in it appearing as though it was floating out in front of the monitor surface, between the viewer and the rest of the display. The right-eye image of the rectangular search surface and search array was 0.30° of visual angle to the right of the left-eye image (uncrossed disparity). This resulted in it appearing as though it floated out behind the surface of the monitor. Finally, for the fixation displays (before presentation of the search array), the fixation point (a 0.7° × 0.7° black plus sign) was presented at the horopter (i.e., zero disparity between the eye images), resulting in it appearing at the surface of the monitor, between the filter surface and the search surface.

The search arrays consisted of 8 or 32 small, near-square rectangles (1.3° × 1.2° of visual angle). The positions of these search items were chosen on the basis of a 6 × 6 matrix of locations that subtended, in total, 10.5° × 11.6° of visual angle. For each item, a random cell from the 36 locations (or from those not already filled) was chosen, and the item was presented within that cell. The center point of the item was jittered randomly within 25% above or below the center point of the cell. This made the search arrays look randomly distributed, without any item overlapping another. A given item always appeared entirely inside or entirely outside of the filtered region.

The luminances of the targets and distractors (summarized in Table 1) depended on whether the items were inside or outside of the filtered region. Notice that when the dark target was outside the filtered region, its luminance was equal to that of the distractors inside the filtered region. Similarly, the luminance of the light target inside the filtered region was equal to that of the distractors outside the filtered region. The dark target inside the filtered region and the light target outside the filtered region did not match any distractor in luminance.

Design. A 2 (target status: present, absent) × 2 (target type: dark, light) × 2 (target location: outside and inside the filtered region) × 2 (set size: 8, 32) within-subjects design was used. Target type and target location were meaningful only for target-present trials. Participants completed nine blocks of 64 correct trials each. Error trials were repeated at some random point later in the block. This resulted in 36 observations per participant in each of the eight target-present conditions and in 144 observations for each of the two target-absent conditions (set sizes: 8 and 32).

Procedure. Each participant completed a single 1-hr session. Before presenting instructions for the main task, each participant completed a screening procedure that was designed to assess whether the person could perceive depth on the basis of binocular disparity alone. On each trial of the

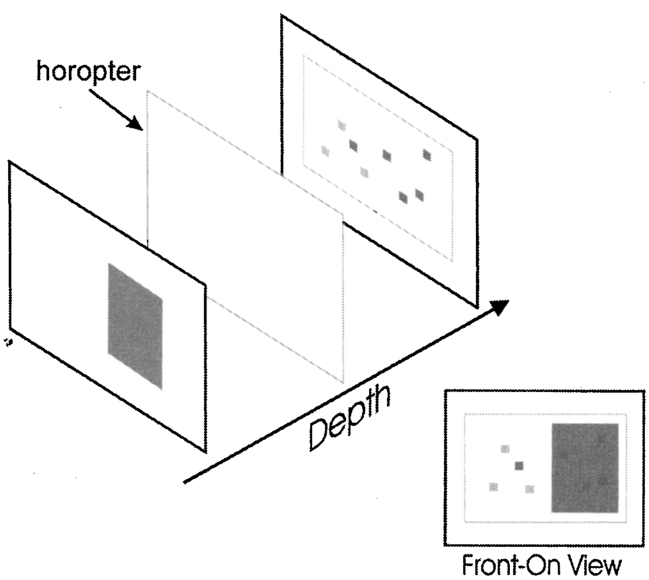

Figure 2. An illustration of the depth depicted through binocular disparity in Experiment 1. In the upper-left portion of the figure is a schematic representation of the depth relationships. The fixation cross (not shown) appeared centered at the horopter. In the lower right of the display is a front-on view of the display without depicted depth. See text for details regarding disparity values.

Table 1
Stimulus Luminances (cd/m²) for Experiment 1

Object	Location: Inside filtered region	Outside filtered region
Dark target	0.8	1.7
Distractor	1.7	3.4
Light target	3.4	7.0

screening test, two 1.3° × 1.2° rectangles were presented side-by-side in 2 of 25 locations in a 5 × 5 matrix of locations. One rectangle was red and the other was blue; color was determined randomly for each trial. One rectangle was presented in the front depth plane (0.3° crossed disparity), and the other was presented in the back depth plane (0.3° uncrossed disparity). The task was to determine whether the left or the right rectangle was in the front depth plane. Participants completed two blocks of 48 trials, one practice block and one test block. Data from the main experiment were kept only from participants who obtained screening-test accuracy scores (percentage correct) greater than or equal to 70% on the test block. Ten participants were eliminated on these grounds. (The large number of eliminated participants depended, in part, on equipment failures. It is unlikely that all of these participants were stereoblind.) The mean percentage correct on the screening procedure for the 20 participants for whom data were kept was 87%, with a range of 70–100%.

After the screening procedure, participants were given a set of written instructions that described the search task. Details of the task were described verbally as well. The task was defined with regard to lightness. Participants were told that they would see displays of gray squares and that most of these would be a medium level of gray but that on some trials, there would be a lighter or a darker gray square present as well. Their task was to report whether one of these lighter or darker gray squares was present or not. They were told that there would be a region that looked like a piece of dark glass floating in front of the display and that some of the squares would appear behind this glass and some would not. Their task, in any case, was to look for the lighter or darker square, regardless of where it appeared. To clarify these instructions, participants were then shown three different sample displays: one with a dark target inside the filtered region, one with a light target outside the filtered region, and one with no target. After these instructions, participants completed one 48-trial practice block. Further clarification of the task was offered during this practice block. Postpractice written instructions emphasized that responses should be made as quickly as possible, while maintaining a 95% or better level of accuracy.

Each trial began with the presentation of the background on the back depth plane, the filter on the front depth plane, and a 0.7° fixation cross on the horopter for 1,000 ms. This initial display was followed by the elimination of the fixation point and the addition of the search array on the background plane. This display remained on screen until the participant responded, at which point the screen went blank. The fixation display for the next trial followed 2,000 ms later.

Results

The mean correct RTs for the target-present trials of Experiment 1 are shown as a function of set size in Figure 3A. A 2 (target type: dark, light) × 2 (target location: inside, outside) × 2 (set size: 8, 32) repeated measures analysis of variance (ANOVA) was conducted on the participant means of these trials. First, RT was nearly invariant as a function of display size for all of the conditions. Consistent with this observation, the main effect of set size was not significant, $F(1, 19) = 3.99$, *ns*. There was, however, a significant interaction between target type and set size, $F(1,$

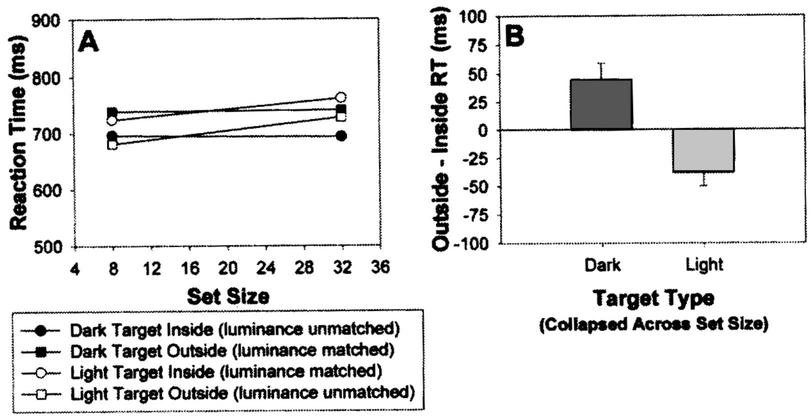

Figure 3. Results from target-present trials in Experiment 1. A: Mean reaction times (RTs) from the correct target-present trials for each of the target type and target location conditions shown as a function of set size. B: Differences in mean RT between conditions with the target outside the filtered region and with the target inside the filtered region for the dark and light targets separately. These data are collapsed across set size. Error bars represent the standard errors of the differences.

19) = 9.20, *MSE* = 1,121.22, $p < .05$, reflecting the fact that the RT-by-set-size slope was slightly negative for the dark target (−0.04 ms per item) as compared with the light target, which was slightly positive (2.63 ms per item). Because this small slope difference across targets was uninfluenced by which region of the display the target appeared in, as suggested by the fact that the three-way interaction was not reliable ($F < 1$), it does not reveal anything regarding the question addressed in this paper. Instead, the pattern of slopes suggests that the dark target may have been, overall, a slightly more salient target than the light target.

Most important for the current study is that the interaction between target type and target location was significant, $F(1, 19) = 15.19$, *MSE* = 4,955.23, $p < .01$. This interaction confirms that search performance was worse (i.e., slower) for the two luminance-matched conditions than for their counterpart luminance-unmatched conditions. In particular, detection of the dark target was more difficult when it was outside than when it was inside the filtered region; detection of the light target was more difficult when it was inside than when it was outside the filtered region.

Figure 3B reveals the nature of the target type by target location interaction more clearly by showing the data collapsed across set size and summarized in terms of difference scores—differences in RT between the outside-the-filtered-region and the inside-the-filtered-region conditions—for the light and dark targets separately. Planned comparisons confirmed that both differences were reliably different from zero, but in opposite directions. Again, the directions of the differences indicate that for each target type, the luminance-matched condition yielded longer RTs than did the luminance-unmatched condition. For the dark target, the difference was greater than zero, 55 ms, $t(19) = 3.18$, $p < .01$, and for the light target, the difference was less than zero, −40 ms, $t(19) = -3.28$, $p < .01$.

All of the same analyses were run on the arcsine transformations of the error rates (ERs) for the target-present trials (ERs given in Table 2). No significant effects that were in a different direction from those in the RTs were revealed.[3]

Finally, the mean correct RTs and the ERs for the target-absent trials are given in Table 3. Although summary data from the target-absent trials will be presented for each search experiment, further analyses of these data will not be presented because they do not provide information concerning the question being addressed in this study.

Discussion

The results of Experiment 1 suggest that visual search may be based at least in part on preconstancy information. The luminance-matched conditions, which were relatively ambiguous at the level of their preconstancy information, yielded slower search times than did the entirely unambiguous, luminance-unmatched conditions. That ambiguity at the preconstancy level could hinder search performance suggests that search processes did access that preconstancy information.

Before concluding that visual search was in fact influenced by preconstancy information, however, some alternative reasons for why Experiment 1 may have produced the results that it did needed to be ruled out. For example, it was possible that the rendered displays did not support lightness constancy in the way that we assumed that they did. If they did not, then the predictions concerning search performance would be inapplicable. This concern was addressed in the next experiment.

Experiment 2

To rule out the possibility that the computer-rendered displays failed to support lightness constancy, we used them to replicate a

[3] Because RT was the main dependent measure and participants were instructed to make their responses as quickly as possible, the purpose of the ER analyses was to provide assurance against drawing conclusions from patterns in the RT data that could have been due to a speed–accuracy trade-off. We therefore present *F* and *t* values for the ER analyses only when there is a significant effect that was not there in the RTs or that was in the opposite direction of that in the RTs.

Table 2
Error Rates (% Incorrect) for Target-Present Trials Across Experiments

Experiment and target	Location: Inside filtered region, Set size 1	Inside filtered region, Set size 2	Outside filtered region, Set size 1	Outside filtered region, Set size 2
Experiment 1				
Dark target	5.45	6.23	11.18	8.09
Light target	3.44	5.00	2.80	7.01
Experiment 3				
Medium target	4.38	9.16	5.70	9.41
Experiment 3a				
Medium target	2.42	9.53	2.58	8.67
	Low-illumination region		High-illumination region	
Experiment 4				
Dark target	3.44	2.29	6.02	8.10
Light target	3.44	2.29	6.02	8.10

Note. Set sizes differed slightly across experiments. See text for actual values.

study by Rock, Nijhawan, Palmer, and Tudor (1992) that also involved lightness constancy but that used "real" stimuli. Rock et al. (1992) showed that the perceptual phenomenon of *grouping by similarity*—the tendency to perceive items that are similar to each other (e.g., in surface color) as grouping together—is based on the perceived characteristic of lightness rather than on the physical characteristic of luminance. This study provided a benchmark for our displays because it was done with gray pieces of paper, external light sources, and cast shadows. If the computer-rendered displays could be shown to yield the same results as these real-object displays did, then the concern that the displays used in Experiment 1 were insufficient to support the types of perceptual effects that lightness constancy usually supports could be reduced considerably.

Participants were presented with rendered displays like those in Figure 4, and their task was to report whether the center column appeared to group with the left set of flanking columns, the right set of flanking columns, or neither. In one condition, hereafter referred to as the *front* condition, a darkened rectangle that simulated a 50% filter was presented floating out in front of the grouping display surrounding the center column (Figure 4A). Like the search displays in Experiment 1, it should have appeared as though the grouping display was being viewed through a transparent gray surface. Given lightness constancy, then, changes in luminance across the filtered and unfiltered regions should have been discounted as being due to the filter. In the critical set of displays of this experiment, luminances were chosen such that the center column matched one set of flanking columns in luminance but, given lightness constancy, matched the other set of flanking columns in lightness (see Figure 4A). Thus, by observing with which set of flanking columns participants tended to group the center column, it could be determined whether grouping by similarity was based on lightness or luminance. In analogous nonrendered displays, Rock et al. (1992) found that participants perceived the center column as grouping with the lightness-matched flanking columns, rather than with the luminance-matched flanking columns.

In a second condition, hereafter referred to as the *back* condition, the luminances in the display were identical to those in the front condition, but the darkened region was presented in depth behind the grouping display (see Figure 4B). In this condition, it should have looked like the grouping display was definitely *not* being viewed through the gray surface. Therefore, changes in luminances across the regions should not have been discounted as due to a filter and instead should have been perceived as actual changes in surface lightness. In analogous nonrendered displays, Rock et al. (1992) found that participants perceived the center column as grouping most strongly with the luminance-matched flanking columns, which in that case also happened to be lightness matched.

Thus, the set of critical displays in this experiment provided the opportunity to test the power of the computer-rendered displays to support perceptions that are associated with lightness constancy. If the displays were sufficient, then grouping preferences should have reversed as a function of whether the filter was perceived in front of or in back of the grouping displays. This would be a compelling set of results, because none of the luminance values would have changed across these two conditions. Thus, the preference reversal would have to depend on perceived values of the stimuli.

Method

Participants. Twenty participants from the same pool as in Experiment 1 were tested. None had participated in Experiment 1, and all were naive as to the purpose of the experiment before participating.

Equipment. The equipment was the same as in Experiment 1.

Task. The task was to indicate whether the middle column grouped with the left two columns, the right two columns, or neither. *Left, right,* and *neither* were indicated by pressing the *z* key, the / key, or the spacebar on the computer keyboard, respectively. There was no speed stress in this task.

Design. The main independent variable was *filter depth* (front, back). On half the trials, the filter appeared in front of the grouping display, and on the other half, the filter appeared behind the grouping display. In addition, on half of all trials, the flanking columns on the left were light gray, and the flanking columns on the right were medium gray. On the other half of the trials, the reverse was true. The luminance of the center column also varied. For the critical one third of the trials (i.e., those described above), the center column was of the same luminance as the

Table 3
Reaction Times (RTs) and Error Rates (ERs) for Target-Absent Trials

Experiment	Set size condition 1: RT (ms)	1: ER (%)	2: RT (ms)	2: ER (%)
1	921	3.0	946	1.6
3	1,167	1.4	1,932	1.1
3a	1,201	1.1	2,238	0.9
4	678	3.1	678	1.8

Note. Set sizes differed across experiments. See text for actual values.

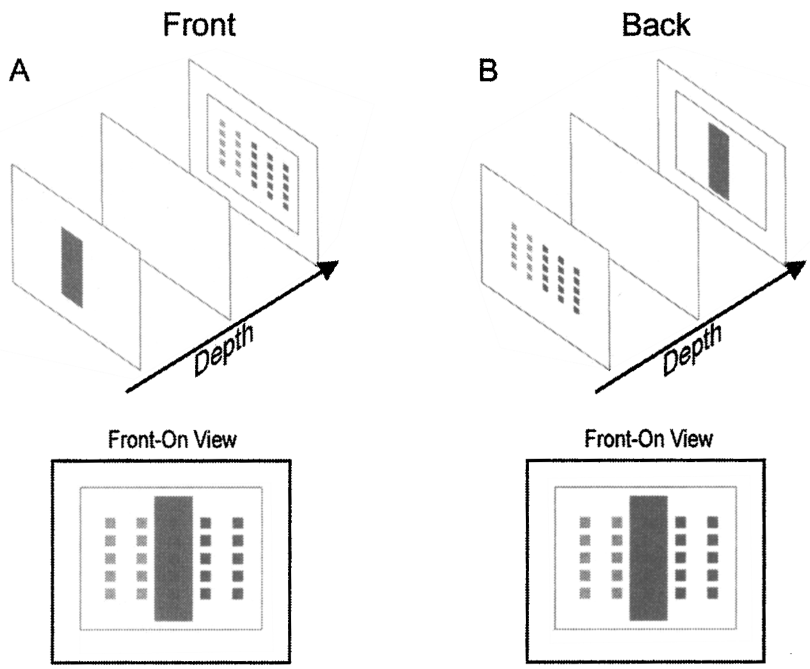

Figure 4. Sample grouping displays for Experiment 2. A: *Front* condition. The filter was presented in the front depth plane, and the grouping display was presented in the back depth plane. B: *Back* condition. The filter was presented in the back depth plane, and the grouping display was presented in the front depth plane. The bottom portion of each panel shows the front-on view, illustrating that the luminances of all of the portions of the display were identical across the two conditions. On the critical trials of this experiment, the luminance of the squares in the darker flanking columns matched that of the squares in the center column, and that luminance was 50% of that of the two lighter flanking columns. This was true for both the front and the back conditions.

darker set of flanking columns and was 50% darker than the lighter set of flanking columns. These were the critical trials because given lightness constancy, when the filter was in front, the center column matched the darker set of flanking columns in luminance but matched the lighter set of flanking columns in lightness. In contrast, when the filter was behind, the center column did not match the lighter set of flanking columns at all and matched the darker set in both luminance and lightness.

The remaining two thirds of the trials were noncritical trials and served only as filler. For one third of the trials, the center column was the same luminance as the lighter flanking distractors, and for the remaining one third of the trials, the center column was a lower luminance than the darker flanking distractors. Trials of this type were not included in the design of Rock et al. (1992) but were included in the present experiment because many more trials were run in this experiment than in that of Rock et al. To reduce the obvious repetition of trial types and to deter participants from identifying the main manipulation, these filler trials were included. They are not discussed further, however.

Our dependent measure was the percentage of the critical trials on which participants reported that the middle column grouped with the lighter flanking columns, the darker flanking columns, or neither. To the extent that grouping is based on lightness, rather than luminance, the center columns should group more with the lighter columns in the front condition and more with the darker columns in the back condition.

Participants completed two blocks of 60 trials each, resulting in 20 observations per participant for each of the critical front and back conditions.

Stimuli. Displays were again viewed through the CrystalEyes glasses from a distance of approximately 60 cm. The stimuli consisted of displays like those shown in Figure 4. A 16.7° × 20.0° light-gray rectangle (8.8 cd/m^2) served as the background. The grouping display, which was superimposed on the background, was a 5 × 5 matrix of 1.3° × 1.2° rectangles that subtended 8.5° × 9.3° of visual angle overall. A darker rectangle (4.3 cd/m^2), which was the rendered filter and covered 15.7° × 2.6° of the visual angle, was centered around the center column. In the front condition, the background and grouping display were presented with a 0.3° uncrossed disparity, and the darkened central rectangle was presented with a 0.3° crossed disparity, causing it to appear as though the darkened rectangle was floating out in front of the grouping display. In the back condition, the grouping display was presented with a 0.3° crossed disparity, and the central rectangle and the background were presented with a 0.3° uncrossed disparity, causing it to appear as though the darkened rectangle was behind the grouping display. The luminances of the squares making up the five columns varied across trials (see *Design* section). The lighter flanking squares had a luminance of 5.3 cd/m^2, and the darker flanking squares had a luminance of 2.7 cd/m^2. The squares in the center columns had a luminance of 2.7 cd/m^2 on the critical trials and of 5.3 and 1.4 cd/m^2 on the lighter and darker noncritical trials, respectively. Note that these luminances were the same for the front and back conditions.

Procedure. Each participant completed a single 1-hr session. Before they performed the main grouping task, participants completed the screening procedure described for Experiment 1. The data for four participants were eliminated on the grounds of results from that procedure. The mean percentage correct on the screening procedure for the 20 participants from whom data were retained was 92%, with a range of 70–100%.

The main part of the experiment began with a set of written and verbal instructions that described the task. Special care was taken to avoid biasing the decisions of the participants during the instruction period. Unfiltered displays were used to describe the grouping task. Participants were told that they would be asked to look at displays of columns and to decide whether the center column appeared to belong with the left or the right flanking columns. To clarify, they were then shown three sample displays with no rendered filter: one with a center column of light-gray squares flanked by light- and medium-gray columns (grouping with the left columns), a similar one with a center column of medium-gray squares (grouping with the right columns), and a display with a center column of dark-gray squares flanked by light- and medium-gray columns (grouping with neither). Participants were warned that there would be a filled rectangle surrounding the center column squares but that their decisions should be based on the squares making up the columns only. Participants were given as much time as they needed to make their decisions. (These instructions were of the same form given to study participants by Rock et al., 1992).

Each trial began with the presentation of the background and the fixation cross for 800 ms. The fixation cross was eliminated, and the filter and grouping display were presented. This display remained on-screen until the participants responded, at which point the display disappeared. The fixation for the next trial followed 1,500 ms later.

Results

The results of Experiment 2 are given in Table 4 in terms of the percentage of the critical trials for which the middle column was reported as grouping with (a) the lighter flanking columns, (b) the darker flanking columns, or (c) neither. These percentages are given for the front and back conditions separately. In the front condition, the middle column was grouped more often with the lighter set of flanking columns than with the darker set of flanking columns (two-tailed Wilcoxon signed ranks test, $Z = -3.84$, $p < .01$). In contrast, in the back condition, the middle column was grouped more often with the darker set of flanking columns than with the lighter set of flanking columns (two-tailed Wilcoxon signed ranks test, $Z = -3.62$, $p < .01$). The *neither* response was used very seldomly.

Discussion

As in the 1992 experiment of Rock et al. with real-object stimuli, grouping by similarity for the computer-based rendered displays was based on the lightness of the items, rather than on the luminance. When the filter was perceived as floating in front of the grouping display, participants grouped the center column with the lightness-matched (lighter) set of flanking columns. When the filter was perceived as floating behind the grouping display, participants grouped the center column with the lightness- and luminance-matched (darker) set of flanking columns. This reversal of grouping preferences occurred despite the fact that no luminance changes accompanied the manipulation of the filter from front to back.

The results of this experiment, then, provided an objective measure of what participants in Experiment 1 reported informally.

Table 4
Grouping Choices (% Sided with Constancy) for Front and Back Displays in Experiment 2

	Display type	
Grouped with	Front	Back
Lighter	84.3	16.5
Darker	10.8	66.8
Neither	4.7	16.7

The rendered displays that were used in Experiment 1 did support lightness constancy. The results obtained in that experiment, therefore, cannot be attributed to a simple failure of lightness constancy due to the use of rendered displays.

Experiment 3

So far, the results suggested that visual search can be influenced by preconstancy information. In Experiment 1, search performance was worse in the luminance-matched conditions than in the luminance-unmatched conditions, and Experiment 2 suggested that this finding was not attributable to a failure of the rendered displays to support lightness constancy in general. Another alternative, however, concerns the fact that in Experiment 1, the targets in the two luminance-unmatched conditions—with the dark target inside the filtered region and with the light target outside the filtered region—were of extreme luminance values. That is, the condition of the dark target inside the filtered region was the lowest luminance that ever occurred in the experiment, and the light target outside the filtered region was the highest luminance that ever occurred in the experiment (see Table 1). These displays may therefore have been privileged at the level of preconstancy information, such that if participants *could* access preconstancy information, they could use it to their advantage. They might, for example, set a low threshold and a high threshold, such that if any luminance higher than the high threshold or lower than the low threshold appeared, that trial would be detected as a target-present trial, without further analysis of the display.

In Experiment 3, the task and stimuli were changed in order to test whether preconstancy information can influence visual search even when this extreme-luminance strategy is unavailable. Participants searched for a medium-gray target among light- and dark-gray distractors. The luminance-matched condition was when the target was outside the filtered region (Figure 5A); here, the luminance of the target was the same as the luminance of distractors inside the filtered region. The luminance-unmatched condition was when the target was inside the filtered region (Figure 5B); here, the luminance of the target matched no other stimulus. Notice that in this case, the target was never of an extreme luminance within the context of the experiment.

The logic was analogous to that of Experiment 1. If search is influenced by preconstancy information even when the extreme-luminance strategy is unavailable, then performance should be worse in the luminance-matched condition than in the luminance-unmatched condition.

Method

Participants. Twenty participants from the same pool as previous experiments were tested. None had participated in the previous experiments.

Equipment. The equipment was the same as in the previous experiments.

Task. The task was to search for a medium-gray target among dark- and light-gray distractors. Responses were indicated in the same way as in Experiment 1.

Stimuli. Displays were similar to those of Experiment 1, except for the luminances of the targets and distractors. These are given in Table 5. Notice that the luminance of the target outside the filtered region was equal to that of light distractors inside the filtered region and that no other luminances matched.

Design. A 2 (target status: present, absent) × 2 (target location: outside filter, inside filter) × 2 (set size: 8, 32) within-subjects design was used. All variables were randomly mixed within blocks of trials. Participants completed 10 blocks of 64 trials each, resulting in 80 observations in each of the four target-present conditions and in 160 observations in each of the two target-absent conditions.

Procedure. The procedure was the same as in Experiment 1. Four participants failed to meet the 70% accuracy criterion for the screening procedure. The mean percentage correct on the screening procedure for the 20 participants for whom the data were kept was 91%, with a range of 80–100%.

In addition to the main experiment, a separate group of 20 participants took part in a control experiment that tested the possibility that the conditions with the target inside and the target outside the filtered region differed in salience simply because of the local-contrast differences across the different sets of luminances. This experiment was identical in design to the main experiment. The displays differed, however. No filter was presented, and all stimuli were presented at the horopter (i.e., with zero disparity). The luminance of the background varied such that in the *light-background* condition, it was the value that was used for the region outside the filter in the main experiment (8.8 cd/m^2), and in the *dark-background* condition, it was the value that was used for the region inside the filter (4.3 cd/m^2). Targets, light distractors, and dark distractors were of their outside-the-filtered-region values (3.1, 6.1, and 0.8 cd/m^2, respectively) in the light-background condition and were of their inside-the-filtered-region values (1.5, 3.1, and 0.4 cd/m^2, respectively) for the dark-background condition. Any differences between the region outside the filter and the region inside the filter in the main experiment that were due to differences in local contrast should have occurred between the dark- and light-background conditions in this control experiment.

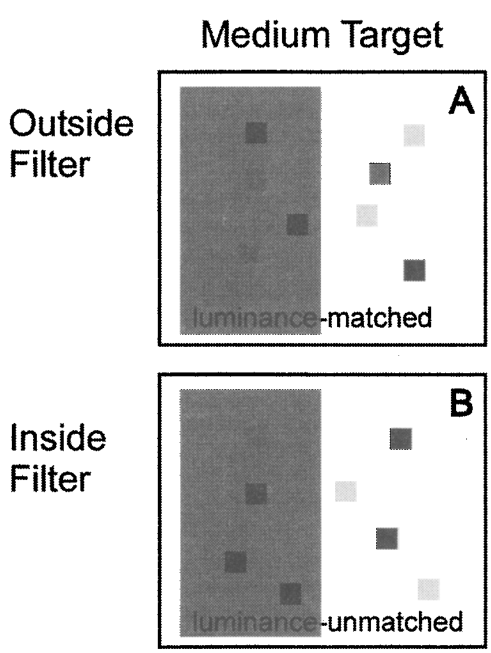

Figure 5. Sample target-present displays from Experiment 3. A: Target outside the filtered region. The luminance of the target matched the luminance of the light distractors inside the filtered region. B: Target inside the filtered region. The luminance of the target matched the luminance of no other stimuli. (Dark distractors outside the filtered region are darker than the target.)

Table 5
Stimulus Luminances (cd/m^2) for Experiment 3

Object	Location	
	Inside filtered region	Outside filtered region
Dark distractor	0.4	0.8
Target	1.5	3.1
Light distractor	3.1	6.1

Results

The mean correct RTs for the target-present trials are shown as a function of set size in Figure 6A. A 2 (set size) × 2 (target location) repeated measures ANOVA run on the participant means revealed a significant main effect of set size, $F(1, 19) = 117.21$, $MSE = 15{,}760.98$, $p < .01$, and a significant interaction between target location and set size, $F(1, 19) = 5.08$, $MSE = 8{,}729.69$, $p < .05$. This interaction confirms that the slope of the function relating RT to set size was reliably greater for the condition with the target outside the filtered region (14.62 ms per item) than for the condition with the target inside the filtered region (10.70 ms per item). The main effect for target location was not significant, $F(1, 19) = 1.82$, $MSE = 47{,}702.71$, *ns.*

Figure 6B shows the analogous data from the control experiment. A 2 (background type) × 2 (set size) repeated measures ANOVA run on the participant means of these data revealed only a significant effect of set size, $F(1, 19) = 28.42$, $MSE = 137{,}711.48$, $p < .01$. These results confirm that the differences observed in the main experiment were not caused simply by differences in local contrast of the two targets in the different regions.[4]

All of the same analyses were run on the arcsine transformations of the ERs for both the main experiment and the control experiment (ERs are given in Table 2). No effects that were different from those in the RTs were found.

Reaction times and ERs from the target-absent trials are given in Table 3.

[4] A similar control was tested for a version of the search task in Experiment 1 involving light and dark targets among medium distractors. The filter region in the search version of the experiment was not presented in depth. Instead, the entire display was rendered in two dimensions. The search results were identical in form to those of Experiment 1; the luminance-matched conditions were slower than the luminance-unmatched conditions. Two versions of the light-background versus dark-background control were run. In one, the background color was blocked such that for half of the blocks, all displays had the dark background, and for the other half of the blocks, all displays had the light background. This version yielded the same findings as did the present control for Experiment 3; search performance was equally good across the different backgrounds. These results ruled out concerns about local contrast. In a second version of the control, light and dark backgrounds were mixed within blocks. In this case, dark targets were found on dark backgrounds more quickly than on light backgrounds, and light targets were found on light backgrounds more quickly than on dark backgrounds. We believe that the difference between the mixed and blocked versions of the control is that the extreme-luminance strategy was useful in the mixed version but not in the blocked version.

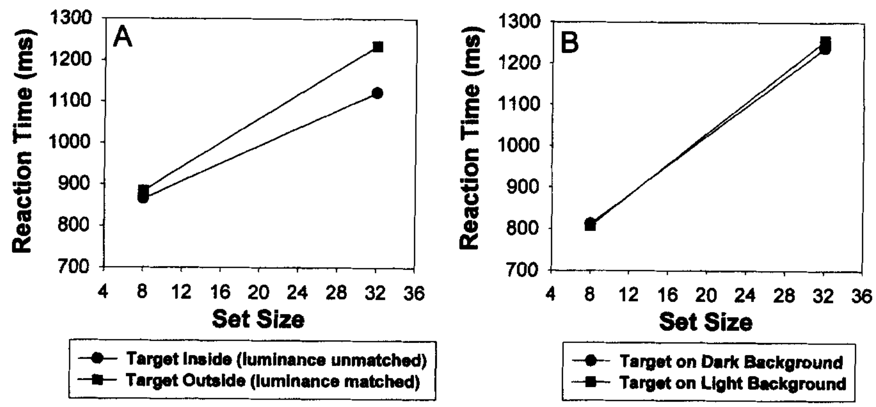

Figure 6. Results from target-present trials in Experiment 3. A: Mean reaction times from correct target-present trials for each of the two target-location conditions, shown as a function of set size. B: Mean reaction times from correct target-present trials for each of the two background conditions in the control experiment.

Discussion

The results of Experiment 3 indicate that preconstancy information influenced search even when the extreme-luminance strategy that was available in Experiment 1 was unavailable. As in Experiment 1, search performance was worse in the luminance-matched condition than in the luminance-unmatched condition. In particular, RT increased more steeply in the condition with the target outside the filtered region than in the condition with the target inside the filtered region. This was true even though the target was never of an extreme luminance.

The basic search task—searching for a medium target among light and dark distractors—was not as efficient as the task used in Experiment 1. Specifically, RT increased as a function of display size in Experiment 3 (12.7 ms per item) but did not in Experiment 1 (0.7 ms per item). This is not surprising because searching for a target among relatively heterogeneous distractors is known to be more difficult than is searching among homogeneous distractors (e.g., Duncan & Humphreys, 1989; Treisman, 1988). A consequence of this difference, however, is that the effect of the luminance match between the target and distractors was manifest in terms of increased time per item (i.e., slope) rather than simply as a shift in overall search time (i.e., intercept). This raises the possibility that the way in which preconstancy information influenced search was different in the two experiments. This possibility will be considered in more detail in the General Discussion. For the moment, the main point is that preconstancy information did influence visual search, even when the extreme-luminance strategy was unavailable.

The next experiment provides a final example of preconstancy information influencing visual search, this time using displays in which the preconstancy information is extremely difficult to perceive.

Experiment 4

In many experimental displays, as well as in many real-world situations, it is possible to perceptually appreciate (i.e., experience and report) both lightness (perceived reflectance) and brightness (perceived luminance). Imagine, for example, a gray square that has a shadow cast across one half of it. You would perceive the square as maintaining a fairly constant lightness across the different regions and, at the same time, perceive the half of the square that is in the shadow as darker (in terms of luminance) than the half of the square that is outside of the shadow. This intuition has been confirmed by research showing, for example, that observers can accurately match a test patch within a random array of patches—called a *Mondrian*—for either lightness or brightness (e.g., Arend & Goldstein, 1987; see also Arend & Spehar, 1993a, 1993b). It is possible, then, that this is why preconstancy information was found to influence visual search in the previous experiments. Specifically, if the preconstancy information is phenomenologically available, then perhaps it is not particularly surprising that it plays a role in guiding attention during visual search. In this final experiment, we tested for the influence of preconstancy information on visual search using displays in which the preconstancy information was difficult to perceive, even with careful scrutiny of the scene.

An example of the basic display that we used, which was developed by Adelson on the basis of principles described in Adelson (1993), is shown in Figure 7. The two squares that are shown in this display are identical in luminance. It is extremely difficult to convince oneself of this match, however. One way to do so is to eliminate the context by, for example, viewing the squares through two small holes cut into a piece of paper such that the rest of the display is occluded. This display provides an example in which the preconstancy information—luminance—cannot be easily perceived by the observer. The question, then, is whether this information will still influence visual search. If so, it would imply that information that is not readily available at a phenomenal level can nonetheless influence how we search through a scene.

Figure 8 illustrates the search displays that were developed based on the display shown in Figure 7. The task was the one involving a light or dark target among medium distractors. This task has two advantages over the medium-target search. First, it yields very efficient search, which increases the probability that we are probing relatively early visual processes. Second, it allows for opposite predictions, with regard to display region, for the dark

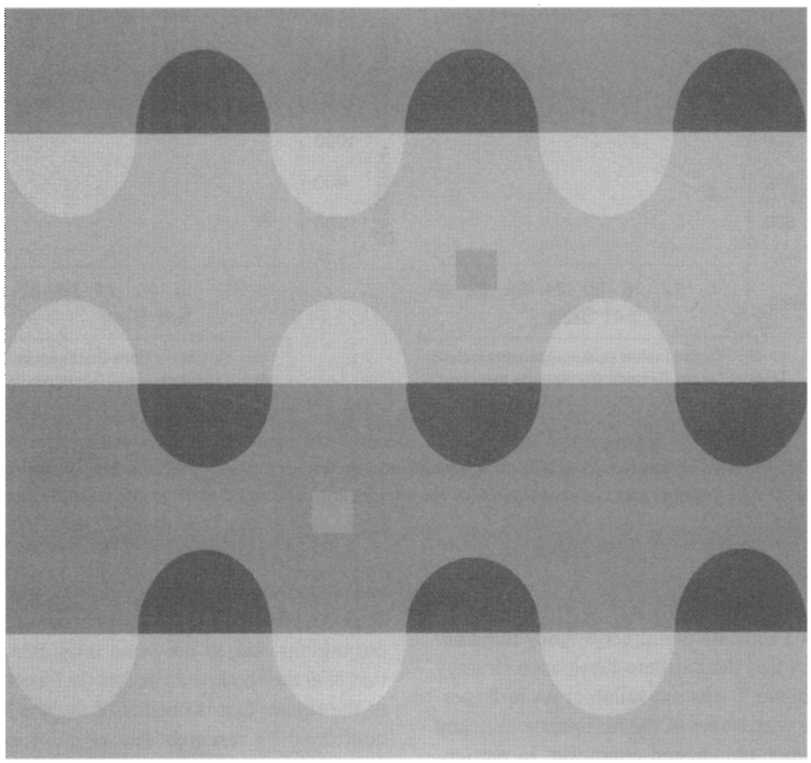

Figure 7. An illustration of a brightness illusion that was developed by Adelson, based on principles discussed in Adelson (1993). The two squares in the display have the same luminance, but they appear to be quite different from each other.

and light targets. This reduces worries regarding artifactual effects of any potential region preferences that subjects may have.

Luminances were chosen in an analogous manner to that of Experiment 1. The dark target in the high-illumination region and the light target in the low-illumination region were the luminance-matched conditions (Figures 8A and 8D). The dark target in the low-illumination region and the light target in the high-illumination region were the luminance-unmatched conditions (Figures 8B and 8C). The predictions, therefore, were also analogous to those of Experiment 1. If preconstancy visual search is based, in part, on preconstancy representations of the scene, then performance in the luminance-matched conditions should be worse than that in the luminance-unmatched conditions.

Method

Participants. Twenty participants from the same pool as those in the previous experiments were tested. None had participated in any of the other experiments.

Equipment. The computer equipment was the same as that used in the other experiments. The CrystalEyes system was not used in this experiment.

Stimuli. The background, which subtended 19.2° × 19.3° of visual angle, included four wavy, *s*-like regions (referred to as *snakes*) that were rendered to appear as though they differed in their transparency conditions (see Figure 8). As for the background pattern, there were two middle full snakes and two flanking half snakes, one at the top and one at the bottom. The distance across the width of a full snake between two outward-pointing bumps was 9.9°, and that between two inward-pointing bumps was 3.1°. The corresponding distances were half that for the two half snakes. The diameter of a bump was 3.2°. Finally, the total length of each snake was 19.2°. The snake regions alternated between dark and light (details about luminances given below). For half of the displays, the order was dark, light, dark, light, and for the other half, the order was light, dark, light, dark. In addition to the wavy background, there were four rectangular regions that looked like regions of relatively high or low illumination (or like differentially transparent surfaces) superimposed on the wavy background regions. Although differential illumination is not the only way that such regions might arise, for convenience of discussion, we will refer to the light and dark superimposed rectangles as ***high-illumination*** and ***low-illumination*** regions, respectively. The illumination regions alternated between low and high in the opposite order from that of the background snake regions behind them. The middle two rectangles subtended 6.4° × 19.3°, and the top and bottom rectangles subtended 3.2° × 19.3°.

The search array, which was made up of near-square items subtending 0.9° × 1.0° of visual angle, was presented entirely within the two middle rectangular regions, one of which was a low-illumination region and one of which was a high-illumination region. The total area of visual angle in which search items could appear was 12.6° × 12.4°. Half of the items in a given display appeared in the high-illumination region, and half appeared in the low-illumination region. The locations of individual items were chosen such that no item appeared in or intersected with any of the bumps in the snake regions.

Luminances within the display were defined based on a set of baseline values for a light target, a medium distractor, and a dark target, as well as, for the background regions, a light-snake region and a dark-snake region. When a stimulus appeared in a high-illumination region, its luminance was 50% greater than its standard value. When a stimulus appeared in low illumination, its luminance was 50% lower than its standard value. Notice

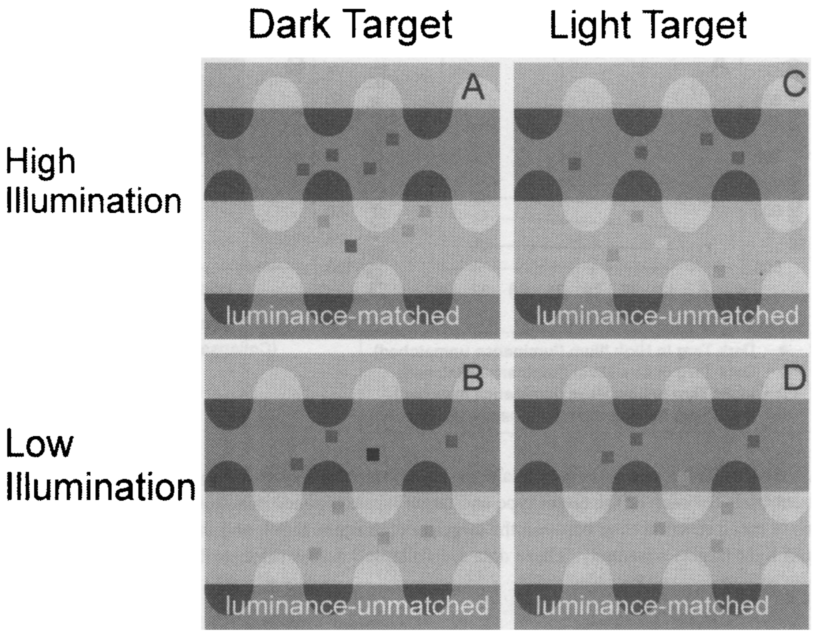

Figure 8. Sample target-present displays from Experiment 4. A: *Dark target in high illumination.* The luminance of the target matched the luminance of the distractors in the low-illumination region. B: *Dark target in low illumination.* The luminance of the target matched the luminance of no other stimulus. C: *Light target in high illumination.* The luminance of the target matched the luminance of no other stimulus. D: *Light target in low illumination.* The luminance of the target matched the luminance of the distractors in the high-illumination region.

that all stimuli appeared in either a high-illumination region or a low-illumination region, so the standard values never appeared in any display. The specific luminances for the various parts of the display and the search stimuli are given in Table 6.

Task. The task was the same as that in Experiment 1: Search for and report, as quickly as possible, the presence or absence of a light or dark target among medium-gray distractors. Again, target presence was reported by pressing a key with the dominant hand, and target absence was reported with the nondominant hand.

Design. The design was the same as that of Experiment 1: a 2 (target: present, absent) × 2 (target type: dark, light) × 2 (target location: high illumination, low illumination) × 2 (set size: 8, 32) within-subject design. Participants completed 12 blocks of 64 trials each, resulting in 48 observations in each of the eight target-present trials and in 192 in each of the target-absent conditions.

Procedure. The procedure was the same as in Experiment 1, except that the test for stereoblindness was eliminated. In addition, a subexperiment was conducted in which the strength of the brightness illusion in these displays was measured by using a nulling procedure. Fourteen participants (different people from those who participated in the main experiment) were recruited for this purpose. Each was presented with displays that were identical to those used in the main experiment, except that only two squares were present, one in the high-illumination region and one in the low-illumination region (like Figure 7). The luminance of one of the two squares was anchored at one of the two critical target values from the main experiment: (a) the light-target-in-low-illumination value or (b) the dark-target-in-high-illumination value. The luminance of the second square was set initially at a random level. Participants controlled the luminance of the nonanchored square via keypresses. They were asked to set the luminance so that the two squares appeared to be of the same gray. Half of the displays were with the high-illumination region on top, whereas the other half were with the low-illumination region on top. In half the trials, the anchored square was the one in the low-illumination region, and in the other half, it was the one in the high-illumination region. Each participant completed 14 trials: 2 practice and 12 from which data were retained.

Table 6
Stimulus Luminances (cd/m^2) for Experiment 4

Object	Illumination level: Low	High
Dark target	10.8	18.0
Distractor	18.0	30.4
Light target	30.4	49.8
Dark-snake background	22.1	36.7
Light-snake background	26.7	44.0

Results

The pattern of results from the search task was very similar to that found in Experiment 1. The mean correct RTs for the target-present trials are shown as a function of set size in Figure 9A. A 2 (target type) × 2 (target location) × 2 (set size) repeated measures ANOVA run on the correct RTs revealed significant main effects of target type, $F(1, 19) = 8.39$, $MSE = 1{,}474.14$, $p < .01$, and target location, $F(1, 19) = 5.16$, $MSE = 1{,}563.98$, $p < .01$, but not of set size, $F(1, 19) = .038$, *ns*. The interaction between target type and set size was not significant, $F(1, 19) = .95$, *ns*, nor was the three-way interaction, $F(1, 19) = 1.56$, *ns*. Critically, the interaction between target type and target location was significant, $F(1, 19) = 85.61$, $MSE = 1{,}963.27$, $p < .01$, confirming that perfor-

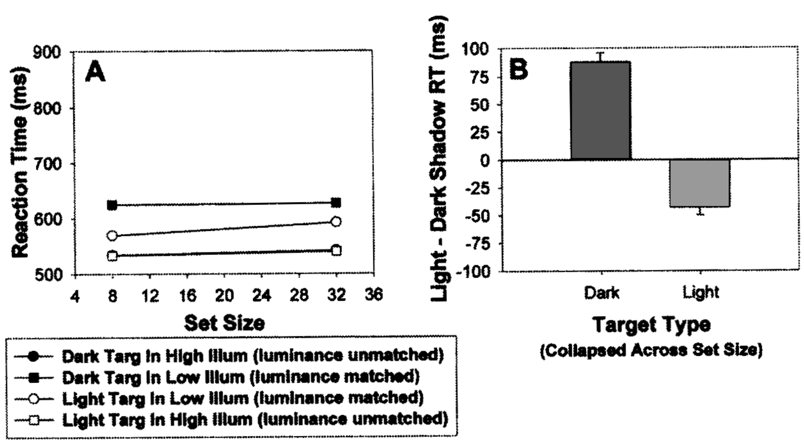

Figure 9. Results from target-present trials in Experiment 4. A: Mean reaction times from the correct target-present trials for each of the target type and target location conditions shown as a function of set size. B: Differences in mean reaction time between the target in high illumination and the target in low illumination for the dark and light targets separately. These data are collapsed across set size. Targ = Target.

mance in the luminance-matched conditions was reliably worse than that in the luminance-unmatched conditions.

Figure 9B shows the differences in RT between the two illumination region conditions—high-illumination RT subtracted from low-illumination RT—for the light and dark targets separately. These data are collapsed across set size. Planned comparisons confirmed that both of these differences were reliably different from zero. As in Experiment 1, the directions of the differences were in opposite directions. For the dark target, the difference was greater than zero (88 ms), $t(19) = 10.44, p < .01$, and for the light target, the difference was less than zero (-44 ms), $t(19) = -6.53$, $p < .01$.

All of the same analyses were run on the arcsine transformations of the ERs for the target-present trials (ERs given in Table 2). No significant effects that were different from those in the RTs were revealed.

The mean correct RTs and the ERs for the target-absent trials are given in Table 3.

Finally, the data from the nulling procedure in the subexperiment indicated that the displays were quite compelling. On average, the luminance settings given by the participants differed from the anchor square by 31%, with a range of 10–50% across the 14 participants.

Discussion

The results of this experiment were perhaps the most striking of the set. Despite having little or no perceptual access to the critical preconstancy information in these displays (i.e., the luminance matches in the luminance-matched conditions), search performance was still strongly influenced by it.

It is interesting to note that the results of this experiment provide a complement to previous results in which visual search was uninfluenced by aspects of the display that, with scrutiny, participants could easily perceive (He & Nakayama, 1992; Rensink & Enns, 1995, 1998). Rensink and Enns (1995) refer to the *preemption* of earlier representations by later representations, such that the earlier interpretations are available only with scrutiny. These then are also examples of dissociations between what can be phenomenologically experienced and what seems to drive search through the scene.

General Discussion

The results of this study indicate that preconstancy information can influence visual search, even when, as in the last experiment, that information is not readily accessible at a phenomenological level. Although postconstancy information is eventually relevant and probably dominant, the fact that preconstancy information can influence search suggests that search processes are engaged early and are based on developing representations of the scene. In the following sections, we consider some of the implications of these findings.

Postconstancy Information Is Not Ignored During Visual Search

First, we wish to emphasize that although these experiments indicate that preconstancy information influences visual search, it does not follow that visual search is uninfluenced by postconstancy information; put another way, it does not follow that visual search is based entirely on preconstancy information. Several previous studies indicate that postconstancy information can influence search. Aks and Enns (1996), for example, looked at the effect of size constancy on search performance. They found that search for a target that was defined by image length (i.e., preconstancy information) was influenced by where in depth the target was perceived to be. This indicates that size constancy was engaged and that the constancy information influenced search. An analogous situation within the present study would be if the target had been defined by a particular luminance, rather than by a particular lightness. Under those task conditions, it seems quite likely that evidence of postconstancy influence on search would be revealed.

Sun and Perona (1996, 1997) argued that visual search can be influenced by lightness constancy, in particular. They noted that

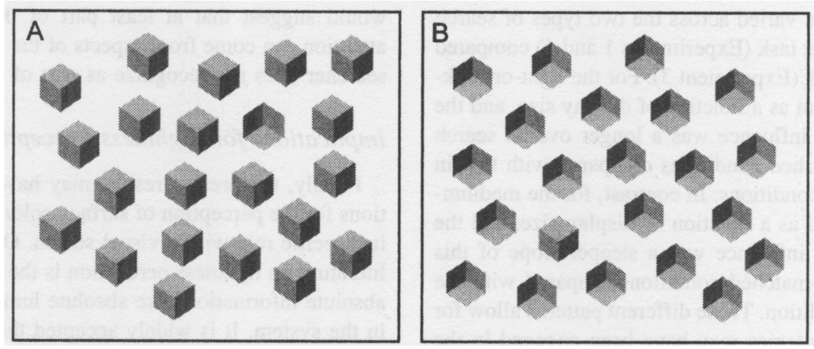

Figure 10. Illustrations of the type of search displays used by Enns and Rensink (1990a) and by Sun and Perona (1996). The display shown in panel A supports more efficient search than that shown in panel B. This is consistent with the hypothesis that the perceptual system makes a default assumption of overhead lighting (Enns & Rensink, 1990a) and may be driven in part by lightness perception (Sun & Perona, 1996).

the effects observed by Enns and Rensink (1990a), cited in the introduction, might have had as much to do with lightness perception as they had to do with 3-D shape-from-shading perception. Using cubes that were given 3-D shape from shading, Enns and Rensink found that detecting the presence of a dark-topped target among light-topped distractors was easier than detecting a light-topped target among dark-topped distractors (see Figure 10). Sun and Perona (1996) noted that to the extent that the light was assumed to be coming from the top—an assumption that the perceptual system appears to make by default (e.g., Kleffner & Ramachandran, 1992; Ramachandran, 1988; Sun & Perona, 1998)—the two search situations represent very different scenes in terms of surface lightnesses. In Figure 10A, the faces of the distractor cubes are perceived as having the same reflectance (i.e., lightness); they just happen to be receiving different amounts of illumination. In contrast, given the same illumination conditions, the faces of the target cube are perceived as having different reflectances. In the context of these postconstancy interpretations of the scene, then, participants were searching for a heterogeneously colored cube among homogeneously colored distractor cubes. Contrast this with the situation in Figure 10B, where given the same analysis, subjects were searching for a homogenous cube among heterogeneous distractor cubes. This contrast could very well lead to the asymmetry in search results that has been observed across these two situations (e.g., Treisman, 1988).

In summary, there is good reason to suspect that even if search processes do engage preconstancy representations of the scene early on in processing, as our data suggest that they do, they are ultimately engaged by postconstancy representations as well. In addition, it is possible that some late interpretations of the scene, such as the surface lightnesses in our displays, are too open to alternative perceptual interpretations to support efficient search. Enns and Rensink (1991) provide some examples supporting this possibility within the context of searching for three-dimensional objects that were rendered by line drawings. Perceptual interpretations of relatively ambiguous aspects of a scene may require full scrutiny to be achieved, and search may for this reason be based in part on earlier representations of the scene.[5]

Constancy Is Not Necessarily Perfect

Color constancy in general and lightness constancy in particular are, like other perceptual constancies, not necessarily perfect (e.g., Brainard, Wandell, & Chichilnisky, 1993; Gilchrist, 1988; Valberg & Lange-Malecki, 1990). Though these processes are referred to as *constancies,* the perception is often only a relative compensation for the spurious aspects of the image. In some circumstances, constancy can be quite poor (e.g., Arend, Reeves, Schirillo, & Goldstein, 1991; Brainard et al., 1993). Thus, given that our displays were rendered on a computer monitor and that they do not represent full-cue conditions, perhaps the evidence of preconstancy influence on search is an artifact of testing the question under these artificial conditions. Or relatedly, perhaps the results simply reflect the slop of information that is left over from what are known to be, even under real-object conditions, imperfect constancy processes.

This is a possibility and would remain one regardless of how much better we could construct our conditions. Despite this observation, however, the present results are revealing with regard to visual perception and visual search. In particular, they reveal that phenomenological experience can be dissociated from the guidance of attention within the visual scene during a search task. This point is most strongly illustrated in the last experiment, in which no amount of verbal persuasion could convince participants that the two squares in displays like that shown in Figure 7 were of the same gray. Yet their search systems seemed to have recognized and responded to that fact. Thus, although the present data cannot rule out the possibility that under the best of conditions, visual search might be based exclusively on postconstancy information, they do highlight this intriguing dissociation.

The Different Search Tasks Seemed to Reveal Different Forms of Preconstancy Influence

Although the results consistently indicate that preconstancy information can influence visual search, the way in which it

[5] We thank Ron Rensink for suggesting this possibility.

influenced search may have varied across the two types of search task: the light-or-dark-target task (Experiments 1 and 4) compared with the medium-target task (Experiment 3). For the light-or-dark-target task, RT was invariant as a function of display size, and the evidence for preconstancy influence was a longer overall search time in the luminance-matched conditions compared with that in the luminance-unmatched conditions. In contrast, for the medium-target search, RT increased as a function of display size, and the evidence for preconstancy influence was a steeper slope of this function in the luminance-matched condition compared with the luminance-unmatched condition. These different patterns allow for speculation about what strategies may have been engaged in the different search situations and thereby about the role that preconstancy information may have played. These speculations, however, are *post hoc* and are presented at the moment merely as possibilities.

For the dark-or-light-target task that was used in Experiments 1 and 4, participants may have used what Bacon and Egeth (1994) called "singleton-detection mode." That is, subjects may have searched for an odd item within homogeneous regions. The existence of the two different regions in the displays—a filtered region and an unfiltered region—may have induced participants to do two singleton-detection searches, one in each region. An opportunity, then, for preconstancy information to influence search would be for it to determine which of the two regions was searched first. It cannot be the case that one of the regions, for example, the filtered region, was always searched first. If it had been, then both the dark target and the light target would have been found and reported more quickly in the filtered region than in the unfiltered region. Instead, subjects may have used the extreme luminance values of the light target outside the filtered region and of the dark target inside the filtered region to guide their initial searches to the regions containing those values. This would be one instantiation of the extreme-luminance strategy described above.

The extreme-luminance strategy was not available for the medium-target task that was used in Experiment 3. Moreover, participants could not have used singleton-detection mode for this task because the displays were heterogeneous. These are both possible reasons for why the influence of preconstancy information took a different form in this experiment than in the other two search experiments. The influence of preconstancy information in the medium-target task can be most easily accommodated within the context of Guided Search (Cave & Wolfe, 1990; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989), which was implicitly invoked in the explanation of the dark-and-light-target task as well. According to the guided search model, attention is pulled around the scene in a bottom-up fashion by stimulus characteristics and is pushed around the scene in a top-down fashion by the goals set by the searcher. The results of Experiment 3 are consistent with the idea that preconstancy information is part of the bottom-up stimulus information that guides search. Specifically, the luminance values of the two versions of the target (both inside and outside the filtered region) could have been prioritized over other luminance values. Because many distractors shared the luminance value of the outside-the-filtered-region version, however, the prioritization resulting from that luminance value would have been less effective in isolating the target from distractors than would the prioritization resulting from the inside-the-filtered-region luminance, which was not shared with any distractors. If this account is correct, then it would suggest that at least part of the bottom-up guidance of attention can come from aspects of the stimulus that the top-down searcher does not recognize as part of the scene.[6]

Implications for Lightness Perception More Generally

Finally, the present results may have at least indirect implications for the perception of surface color in general, rather than just its specific role within visual search. One of the issues within the literature on lightness perception is the question of whether or not absolute information, like absolute luminance, is ever represented in the system. It is widely accepted that as observed by Wallach (1948), lightness perception is determined by the relative luminances of stimuli to their surroundings, rather than by absolute luminances of separate regions. What is not agreed upon is where the relational information comes from. Given Wallach's conceptualization, it was assumed that the ratio of the figure to ground luminances was what was critical and that this was established on the basis of the absolute luminances of the different regions as they were registered at the retina. Gilchrist and his colleagues have referred to this conceptualization as the "*photometer metaphor*" (Gilchrist, 1994; Gilchrist et al., 1983) because it is as if early visual mechanisms act as a photometer to measure the amount of light coming from a given region. An alternative conceptualization is that absolute luminance is never represented in the system and that the relational representations are established via an integration of all the edges and illumination gradients in the scene (Gilchrist et al., 1983). An analogy offered by Gilchrist (1994) for this alternative is that of taking the weight ratio of two objects by "suspending them from opposite ends of a seesaw and bringing them into balance by adjusting the location of the fulcrum" (pp. 5–6). By so doing, the actual weight of neither object is needed for the establishment of the ratio between them.

If the absolute luminances in a scene are never represented in the visual system and if absolute luminance constitutes the preconstancy information to which we have been referring throughout this paper, then the answer to the question initially posed might have been assumed to have had a foregone conclusion. In particular, search would necessarily be based entirely on postconstancy information because there would be no preconstancy information in the system to influence search. The present findings, however, suggest a different conclusion because search appears to have been consistently influenced by preconstancy information.

Do the present results imply that absolute luminance is represented in the system, supporting the photometer metaphor? No, not necessarily. Although a representation of absolute luminance would constitute a sort of preconstancy information and although luminance has been a convenient vehicle for discussing preconstancy information, it is not necessarily the only type of information that could fall into that category. The fact that constancy can be imperfect under the integrative alternative (Gilchrist, 1988) means that there must be other constancy-unresolved representa-

[6] Neither of the explanations offered here are dependent on the specifics of guided search. They appeal to general concepts that are common among many different models of visual search (e.g., Duncan & Humphreys, 1989; Treisman & Sato, 1990). The language of the guided search model, however, provides a particularly convenient vehicle for discussing these concepts.

tions that could be the source of influence in the present experiments. For this reason, the present results can offer nothing definitive toward this debate.

That being said, however, these results are consistent with the possibility that visual search is a task that could allow for the probing of representations that might be inaccessible to the tasks used in more traditional perception experiments. To be clear, studies of surface-color perception most often use tasks in which observers carefully scrutinize displays for as long as they like and then report on aspects of their phenomenological experience (for interesting exceptions to this, see Craven & Foster, 1992; Foster, Craven, & Sale, 1992). In contrast, visual-search tasks require participants to respond to the displays as quickly as possible. Moreover, participants do not, as part of the task, report on their phenomenological experience of the displays. Thus, it is possible that as far as the part of the perceptual system that supports phenomenological experience is concerned, there is functionally no representation of the absolute luminances because it has no access to them. To other parts of the perceptual system, however, including some that guide attention through a scene, for example, absolute luminance may be accessible. If such an account held, then no evidence from traditional perception experiments that require the explicit report of the phenomenology could reveal the existence of these representations.

We present this possibility as worthy of consideration in light of the present results, not as a conclusion to be drawn from them. They only offer the intriguing possibility that by probing the system with what might be described as more implicit measures, previously unrecognized representations might be revealed.

Conclusions

In summary, at least with regard to lightness constancy, preconstancy information can influence the progress of search through a visual scene. This is true even when that preconstancy information is not readily available at a phenomenological level. This finding, in combination with previous evidence that postconstancy information also influences search, suggests that visual search processes are engaged early and are based on developing representations of the scene.

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