Psychonomic Bulletin & Review
2006, 13 (1), 22-32

Inhomogeneous surrounds, conflicting frameworks, and the double-anchoring theory of lightness

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The empirical question of whether or not the lightness of a region is accounted for purely by the average luminance of its surround has a complex answer that depends on whether such a region is an increment, a decrement, or intermediate relative to the luminances of the contiguous surfaces. It is shown here that a new model of lightness, based on anchoring principles, predicts and clarifies such intricacies. In this model, the luminance of the target region determines its lightness in two ways: indirectly, by causing it to group with parts of its surround and thus defining the nested frameworks to which it belongs; and directly, by anchoring it to the highest luminance and to the average surround luminance in each of these frameworks. Inter- and intraindividual differences in lightness assessment are shown to emerge under grouping conditions that create unstable, conflicting frameworks.

Because the lightness of a figure depends on both its luminance and the luminance of its context, when neither changes, the figure's lightness is not expected to change either. Not surprisingly, two squares cut from the same gray paper and placed on two identical mid-gray backgrounds appear to have the same lightness.

Imagine now that one of the two backgrounds is replaced by a simple checkerboard composed of two white checks and two black checks. The average luminance of the background is the same as before, so the square on the checkerboard should still look identical to the square on the homogeneous surround; in other words, the checkerboard should work as an *equivalent background*. However, it has been shown that this is not always the case: When a figure is moved from a homogeneous surround to an inhomogeneous surround of the same average luminance, its lightness may change. This depends on whether the luminance of the figure is higher than, lower than, or intermediate between (Figure 1, top left, top right, and bottom displays, respectively) the luminances of the checks that compose the checkerboard.

This article is divided into two parts. In the first, I consider two important works on this topic (Bruno, Bernardis, & Schirillo, 1997; Schirillo & Shevell, 1996) and describe their findings, which, to date, have not received a comprehensive explanation. I also show that, under certain conditions (Melfi & Schirillo, 2000; Schirillo & Shevell, 1996), the differences between subjects are so remarkable as to demand interpretation. In the second part, the phenomenon of equivalent backgrounds is described from the standpoint of a new model of lightness (Bressan, in press) derived from the theory of Gilchrist et al. (1999) and based on luminance anchoring principles. I show that within such an approach (but not within the original anchoring model), the data and the individual differences find an explanation.

EMPIRICAL DATA

The data analyzed in the present article come from two works (Bruno et al., 1997; Schirillo & Shevell, 1996) in which complementary methods were used. In both, a patch centered on a uniform background was compared with a patch centered on a checkerboard. Bruno et al. kept the patches constant (same luminance) and changed the luminance of the uniform background. The checkerboard could be made of two, three, or four regions of different luminances.[1] If the lightness of the patches had been influenced only by the average surround luminance, the uniform background that made the two patches look the same (henceforth the *lightness-equivalent surround*) would have had the same luminance as the average of the checkerboard.

Schirillo and Shevell (1996) kept the backgrounds constant (same average luminance) and had subjects change the luminance of the patch on the checkerboard until it looked equal to the patch on the uniform background. The inhomogeneous surround was composed of four regions and two luminances, as in Figure 1, and contrast was varied. If the patch lightness had been affected only by the average surround luminance, the two patches would have been matched in luminance (across contrast values). A graphical

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I am indebted to Peter Kramer, Alan Gilchrist, and Nicola Bruno for their careful reading of the manuscript and their many constructive criticisms. Any remaining mistakes are my own. Correspondence concerning this article should be addressed to P. Bressan, Dipartimento di Psicologia Generale, Università di Padova, Via Venezia 8, 35131 Padova, Italy (e-mail: paola.bressan@unipd.it).

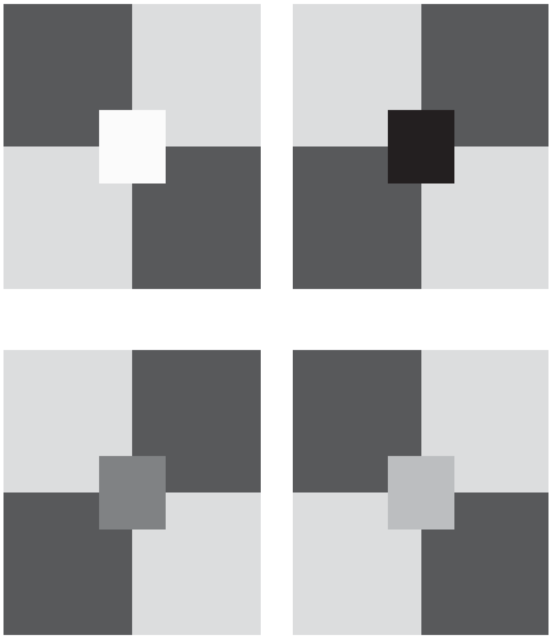

Figure 1. Relative to the checks that compose the checkerboards, the central patches represent a full increment (top left), a full decrement (top right), a partial increment (bottom right), and a partial decrement (bottom left). See text for details.

representation of Schirillo and Shevell's results is shown in Figure 2. For decremental data, dashed horizontal lines have been added to show the matches that would indicate that the effect of the inhomogeneous surround was accounted for by its space-averaged luminance.

The findings of these two studies are compared below. Bruno et al.'s (1997) results are reported under the heading "Variable-surround evidence," and those of Schirillo and Shevell (1996) under the heading "Variable-patch evidence." Note that observers were asked to match *lightness* in the first work and *brightness* in the second. In principle, the distinction between lightness and brightness is immaterial here. Since the lightness of a region is defined as its brightness relative to the brightness of a perceptually "white" region under the same illumination, lightness and brightness coincide. However, as we will see, the way in which the lightness task was described to naive observers explains an apparent contradiction in Bruno et al.'s data.

In the present article, *full increment* refers to a square on checkerboard whose luminance represents an increment relative to the checkerboard's average luminance, as well as to both of the luminances that compose the checkerboard (see Figure 1, top left display). *Partial increment* indicates a square on checkerboard whose luminance represents an increment relative to the checkerboard's average luminance and is between the luminances of the checks, but closer to that of the brighter check than to that of the dimmer check (see Figure 1, bottom right display). *Partial decrement* refers to a square on checkerboard whose luminance represents a decrement relative to the checkerboard's average luminance and is between the luminances of the checks, but closer to that of the dimmer check than to that of the brighter check (see Figure 1, bottom left display). Finally, *full decrement* refers to a square on checkerboard whose luminance represents a decrement relative to the checkerboard's average luminance, as well as to both of the luminances that compose the checkerboard (see Figure 1, top right display).

Full Increments

Variable-surround evidence. A patch of 75 cd/m^2 was centered on a surround divided vertically into two halves, one of 30 cd/m^2 and one of 70 cd/m^2. Any uniform decremental surround (20–60 cd/m^2) worked as a lightness-equivalent background—that is, in a same–different forced choice task, the patch on the inhomogeneous surround was judged equal to the patch on all uniform decremental surrounds, regardless of their actual luminance. However, in a lighter–darker forced choice task, there was a bias toward seeing the patch on the inhomogeneous surround as *darker* than the patch on all uniform decremental surrounds. The luminance of the uniform surround on which the patch appeared neither lighter nor darker was about 76 cd/m^2. This value is considerably larger than the value of the luminance-equivalent background, whether this is taken to be the arithmetic (50 cd/m^2) or the geometric (about 46 cd/m^2) space average.

Variable-patch evidence. Patches on checkerboard that represented increments relative to both the luminances of the checkerboard were seen as equal to patches set on the uniform luminance-equivalent surround. This can be seen in Figure 2, in which full increments are represented by open symbols above the two thick lines in each panel; measurements fall roughly along horizontal lines.

Conclusions. The results of the lighter–darker task in Bruno et al.'s (1997) experiment suggest that a patch on checkerboard appears slightly *darker* than an identical patch on a luminance-equivalent background. In contrast, Schirillo and Shevell's (1996) data indicate that a patch on checkerboard appears *equal* to an identical patch on a luminance-equivalent background.

Partial Increments

Variable-surround evidence. A patch of 60 cd/m^2 placed on a surround divided into three sections (30, 50, and 70 cd/m^2) appeared darker than an identical patch on a luminance-equivalent surround; the lightness-equivalent background was 66 cd/m^2.

Variable-patch evidence. Patches on checkerboard whose luminance was closer to the luminance of the brighter check (such as patches of relative luminances of 60, 70, or 80 on a checkerboard whose checks were 10 and 90) were seen as darker than equal patches set on luminance-equivalent surrounds. In Figure 2, partial increments are represented as open symbols between the two thick lines in each panel; data lines slope upward.

Conclusions. Patches on checkerboard that represented partial increments were seen as darker than identical patches on uniform surrounds.

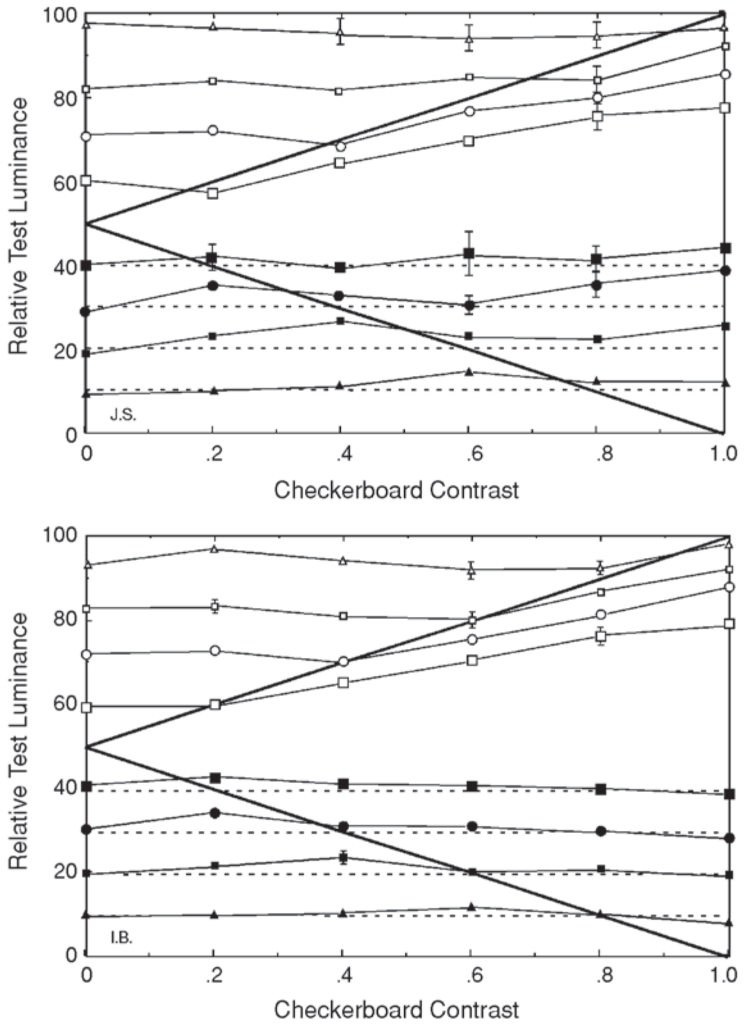

Figure 2. Results of the experiment of Schirillo and Shevell (1996). The graph plots the brightness matches of a patch on checkerboard to a patch on a uniform surround of the same space-averaged luminance, as a function of checkerboard contrast. In each panel, the two diverging thick lines show the luminance of the checks. Open symbols indicate full increments (above the diverging lines) and partial increments (between the diverging lines); solid symbols indicate full decrements (below the diverging lines) and partial decrements (between the diverging lines). Top panel: Subject J.S. Bottom panel: Subject I.B. (From "Brightness Contrast From Inhomogeneous Surrounds," by J. A. Schirillo and S. K. Shevell, 1996, *Vision Research, 36*, p. 1785. Copyright 1996 by Elsevier. Redrawn after Figure 2 of Schirillo & Shevell, 1996.)

Partial Decrements

Variable-surround evidence. A square of 40 cd/m^2 was placed on a surround divided into three sections (30, 50, and 70 cd/m^2). The patch on the inhomogeneous background appeared darker than the patch on the luminance-equivalent uniform surround; the luminance of the lightness-equivalent background was 52 cd/m^2. This value is slightly larger than the arithmetic average (50 cd/m^2) and definitely larger than the geometric average (about 47 cd/m^2).

Variable-patch evidence. Schirillo and Shevell (1996) reported that patches on checkerboard whose luminance was closer to the luminance of the dimmer check (such as patches of relative luminances of 20, 30, or 40 on a checkerboard whose checks were 10 and 90) were seen as about as light as identical patches set on luminance-equivalent surrounds. However, inspection of Figure 2 shows that this was true only for the naive subject I.B. and not for the experienced subject J.S. Partial decrements are represented as solid symbols between the two thick lines in each panel. Clearly, I.B.'s matches fall along horizontal lines. On the other hand, the matches of J.S. are much more variable and tend to oscillate around a value quite above the respective dashed line. Judging by the size of the standard error bars, 9 of 14 data points appear significantly above the dashed line; no point appears below the dashed line.

Conclusions. In Bruno et al.'s (1997) work, patches on checkerboard that represented partial decrements were seen as darker than identical patches on uniform surrounds. In Schirillo and Shevell's (1996) work, the means and *SD*s of the matches made by the experienced subject seem to indicate some unstable effect in the same direction.

Full Decrements

Variable-surround evidence. A square of 25 cd/m^2 was placed on a surround divided into two parts (30 and 70 cd/m^2). The patch on the inhomogeneous background appeared darker than the patch on the luminance-equivalent uniform background; the luminance of the lightness-equivalent background was 53 cd/m^2.

Variable-patch evidence. The matches for full decrements (i.e., those for patches of relative luminances of 10, 20, or 30 on a checkerboard whose checks were 40 and 60) show an increase with checkerboard contrast, as can be seen in Figure 2 (solid symbols below the two thick lines in each panel).

Conclusions. Patches on checkerboard that represented full decrements were seen as *darker* than identical patches on uniform surrounds.

INHOMOGENEOUS SURROUNDS FROM AN ANCHORING PERSPECTIVE

Simultaneous lightness contrast is stronger on articulated surrounds than on uniform ones (Arend & Goldstein, 1987; Bressan & Actis-Grosso, 2006; Lotto & Purves, 1999; Schirillo, 1999), a finding that can be accommodated within various theories of lightness (see, e.g., Adelson, 2000; Gilchrist et al., 1999; Yang & Purves, 2004). However, as we have seen, the data on equivalent backgrounds form a more complicated and partly confused pattern. They are in agreement on partial increments and full decrements but look muddled on full increments and partial decrements. The only model in which the problem of equivalent backgrounds has been directly considered, and in which an attempt has been made to explain at least part of these findings, is Gilchrist et al.'s anchoring theory. Here, I am going to show that, although they cannot be explained by the anchoring theory in its present form, these data make sense in a revised version of the theory, based on double anchoring (Bressan, in press).

The anchoring theory of lightness (Gilchrist et al., 1999) assumes that a scene is segmented into perceptual groups, or frameworks, on the basis of Gestalt grouping principles. Frameworks can be local or global. The lightness of any given surface is a weighted average of the lightnesses of the surface when anchored to (1) its local framework and (2) the global framework. Within each framework, the role of anchor is always assigned to the highest luminance, which receives a value of "white." All other regions are perceived as shades of gray, depending on their luminance ratio to such white.

Full Increments

The results of the lighter–darker task in Bruno et al.'s (1997) work show that a square on checkerboard appears darker than an identical square on a luminance-equivalent uniform surround. The anchoring model cannot explain this because both squares represent full increments. As such, they represent the highest luminance both locally and globally, and should hence appear to be equally white.

Partial Increments, Partial Decrements, and Full Decrements

A square on checkerboard whose luminance is lower than the luminance of at least one of the checks is seen as darker than an identical square on a luminance-equivalent uniform surround. At first sight, the anchoring model would seem to make the correct prediction in this case. The lightness of the square on the uniform surround is computed as a ratio to the surround luminance, which is the local highest luminance; however, the lightness of the square on the checkerboard is computed as a ratio to a higher value—namely, the luminance of the bright checks, which is the local highest luminance. It follows that, in the local framework, the square on the checkerboard should be perceived as considerably darker. More precisely, the two squares would appear locally identical when and only when the uniform surround has the same luminance as the bright checks. On the other hand, in the global framework both squares would be anchored to the bright checks, producing luminance matching and, hence, a dilution of the difference.

This explanation, however, fails to predict the remarkable difference between partial increments and partial decrements (see the symbols between the two thick lines in each panel of Figure 2). The data lines for partial increments (open symbols) slope steeply upward, whereas those for partial decrements (solid symbols) clearly do not. Both data lines ought to slope upward, because increasing checkerboard contrast raises the highest luminance, and should thus enhance the local darkening of the square on checkerboard relative to the square on the uniform surround.

INHOMOGENEOUS SURROUNDS FROM A DOUBLE-ANCHORING PERSPECTIVE

The double-anchoring model of lightness (see the Appendix for a compact formal presentation and Bressan, in press, for a detailed exposition) is a development of the anchoring model of Gilchrist et al. (1999). Within each framework, objects are independently anchored to the highest luminance *and* to the average luminance of their surround, which are both given a default value of "white." Each region, then, receives two independent lightness assignments, determined by its luminance ratios to either anchor and appropriately weighted to express the relative importance of the surround and highest luminance steps. The final lightness value of a region in a framework is the weighted average of the values computed at the two steps.

The final lightness value of a region in the scene is the weighted average of the values computed for that region within each framework.

Frameworks can be determined by listing the spatial and photometric grouping factors that link the target region to the rest of the scene. Examples of spatial factors are adjacency and good continuation (T-junctions). Examples of photometric factors are luminance polarity and similarity (Masin, 2003; see also Beck, Graham, & Sutter, 1991; Hochberg & Silverstein, 1956; Quinn, Burke, & Rush, 1993; Rock, Nijhawan, Palmer, & Tudor, 1992). *Luminance polarity* means that, other grouping forces being equal, grouping will tend to occur preferentially between regions with the same contrast sign. *Luminance similarity* means that, other grouping forces being equal, grouping will tend to occur preferentially with the region (or regions) whose luminance is closer to that of the target. When luminance polarity and luminance similarity are pitted against each other, for some observers grouping is affected prevalently by one of the two, and for other observers equally by both, as is shown very clearly by Masin. A target will not simultaneously group with regions representing opposite contrast polarities (independent evidence is presented in Bressan, 2006). In this case, grouping will instead occur with the region whose luminance is closer to that of the target.

Two frameworks are of interest in the stimuli used by Schirillo and Shevell (1996). The first is the *local framework* (test patch plus the set of checks with which the target is expected to group via the principle of luminance similarity; in the case of the comparison patch, the weight of this framework is always zero, because there are no checks). The second is the *superlocal framework* (test patch plus checkerboard, or comparison patch plus its uniform surround; here, grouping is based on the principle of adjacency). In either framework, we must take into account two luminance ratios: the ratio of the patch to the highest luminance (highest luminance step) and the ratio of the patch to the average luminance of the surround (surround step). In the model, the *surround* of a target in

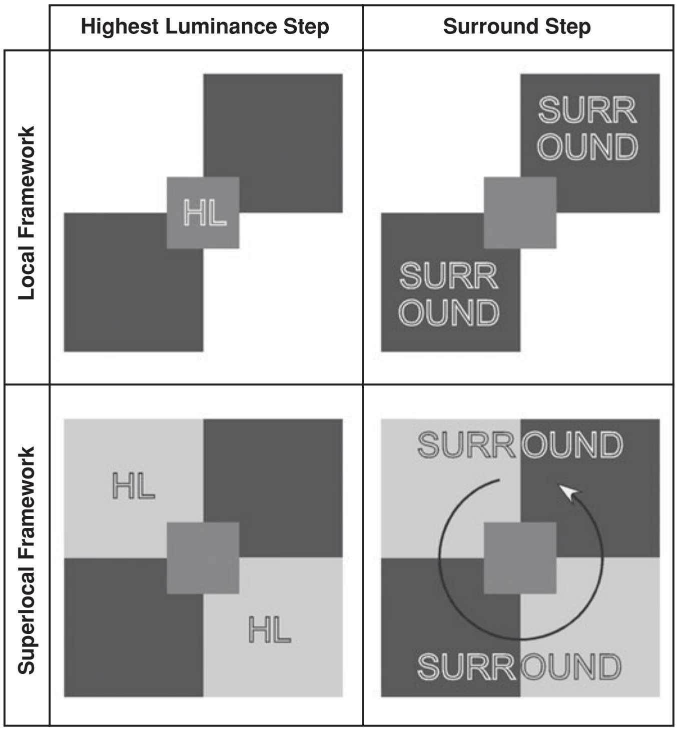

Figure 3. Grouping in a partial-decrement display according to the double-anchoring model. The central square participates in two nested frameworks: the local framework (top panels) and the superlocal framework (bottom panels). Within each framework, it receives two lightness assignments: one at the highest luminance (HL) step (left column), which is determined by its luminance ratio to the highest luminance; and the other at the surround step (right column), which is determined by its luminance ratio to the surround. The final lightness value of the square is a weighted average of these four values (see the Appendix). The diagram indicates which regions serve as highest luminances and as surrounds in the two frameworks. In the local framework, the surround is the luminance of the dim checks; in the superlocal framework, the surround is the average luminance of the checkerboard.

a framework means the contextual regions. Here, then, we will consider as surround the luminance of the more similar checks in the local framework, and the average luminance of the checkerboard in the superlocal framework (see Figure 3).

The bright and dim checks represent opposite contrast polarities relative to the target in partial-increment and partial-decrement displays, and identical contrast polarities relative to the target in full-increment and full-decrement displays. Hence, the local framework for partial increments and decrements (based on luminance polarity and similarity) is stronger than the local framework for full increments and decrements (based on luminance similarity only). This implies that, in the latter displays, local effects (a slight and unstable local darkening in the case of the full increment on checkerboard, apparent in Figure 2 and in the lighter–darker task of Bruno et al.'s (1997) experiment; and a slight dilution of darkening in the case of the full increment on checkerboard) will have little impact on the final average. For the sake of simplicity, then, in the case of full increments and decrements we will take into account lightness assignments in the superlocal framework only.

Let us now see how these concepts help to explain the equivalence of uniform and inhomogeneous surrounds for some luminance hierarchies, but not for others.

Full Increments

A region that represents a luminance increment relative to its surround is always locally white at the highest luminance step, because it is the local highest luminance, and superwhite at the surround step, because it is an increment relative to a surround defined as white. (In the model, the term *superwhite* describes any lightness value larger than that of white, and as a final percept it appears as a glowing, illuminated, or luminous white.) Such superwhite assignment is determined by the luminance ratio of the region to the *average* surround luminance, and is therefore an inverse function of the latter. It follows that fully incremental patches on checkerboard will appear identical to equal patches set on uniform surrounds of the same average luminance. This is what Schirillo and Shevell (1996) found (Figure 2, roughly horizontal lines for full increments). Note that their subjects were asked to match the *brightness* of the comparison patch—that is, to adjust the patch on checkerboard until it appeared identical to the comparison.

Bruno et al. (1997) reported that (1) in the same–different task, any uniform decremental surround worked as a lightness-equivalent background and (2) in the lighter–darker task, the luminance of the lightness-equivalent background was approximately 76 cd/m^2 (i.e., it was essentially the same as the luminance of the patch). These data also fit the double-anchoring model. In fact, Bruno et al.'s subjects were asked to judge the *lightness* of the patches—that is, to indicate whether or not the patches appeared to depict surfaces cut from the same paper (same–different), or to indicate which patch appeared to depict a lighter shade (lighter–darker).

In the double-anchoring model, a 75-cd/m^2 square will look locally white on a 75-cd/m^2 background and superwhite on any decremental background. When people are asked whether the square set on a checkerboard seems cut from the same or from different paper as an identical square set on any decremental uniform background, they will answer "same." Both patches look like pieces of the same white paper, because the lightness scale goes from black to white, and superwhite appears as a glowing white, not as a separate color. But when people are asked to decide which patch is lighter in a forced-choice task, they will of course pick the superwhite patch over the white patch. Incidentally, the latter result is consistent with the existence of simultaneous contrast with double increments (Bressan & Actis-Grosso, 2001, 2006).

Full Decrements

A fully decremental patch on a checkerboard is seen as darker than an equal patch on the luminance-equivalent surround. In the model, this happens because at the surround step the two patches are compared to identical luminances (the average luminances of their surrounds), but at the highest luminance step they are not. The lightness of the patch on the uniform surround is computed as a ratio to the surround luminance (the local highest luminance), but the lightness of the patch on checkerboard is computed as a ratio to a higher value—that is, the luminance of the brighter check (the local highest luminance). It follows that the patch on the checkerboard will appear darker than the patch on the luminance-equivalent surround, and that the higher the luminance of the brighter check, the darker the patch will appear. This can be seen very well in Figure 2, where the lines for full decrements (solid symbols below the two thick lines in each panel) slope gently upward; observers must increase the luminance of the patch on checkerboard to make it look the same as the patch on the uniform surround.

Partial Increments and Partial Decrements

In the model, patches that are intermediate with respect to the checkerboard's luminances receive a lower local lightness assignment than patches on luminance-equivalent uniform surrounds. The reason is that, at the highest luminance step, patches on checkerboard are anchored to the brighter check, whose luminance is higher than that of the uniform surround.

This seems to imply that in Schirillo and Shevell's (1996) experiment the data lines for both partial increments and partial decrements ought to slope upward. This is clearly the case for partial increments, but not for partial decrements (see, respectively, the open and solid symbols between the two thick lines in each panel of Figure 2). To understand why this happens, notice that, in partial-increment and partial-decrement displays, the bright and dim checks represent opposite contrast polarities relative to the target. On the basis of the grouping cues of luminance polarity and similarity working in tandem, partly incremental patches (60–90) tend to group with the brighter checks (70–100) rather than with the dimmer checks (30–0). The patch on checkerboard thus participates in two nested frameworks, which we have called *local* (target plus brighter checks) and *superlocal* (target plus checkerboard).

For partial increments, the lightness assignments that the target receives in the two frameworks go in the same direction. In the superlocal framework, the target darkens, because at the highest luminance step it is anchored to the brighter check. In the local framework, the target darkens even more, because it is anchored to the brighter check both at the highest luminance and at the surround steps. The result is that the effect, which would be present even without luminance grouping, is expected to increase further. It follows that the slope of the data lines for partial increments will tend to be much steeper than the slope of the data lines for full decrements (which agrees with the data; in each panel of Figure 2, compare open symbols between the diverging lines with solid symbols below the diverging lines).

For partial increments, then, luminance grouping leads to an increase of the illusion. The same process, however, yields opposite results for partially decremental patches (10–40), which tend to group with the dimmer (0–30) rather than with the brighter (70–100) checks. Again, this gives rise to a local framework (target plus dimmer checks) and a superlocal framework (target plus checkerboard). These two frameworks are represented in the diagram of Figure 3. Now, the lightness assignments that the target receives in the two frameworks, relative to an identical target on the uniform surround, go in opposite directions. In the superlocal framework, the target darkens, because at the highest luminance step it is anchored to the brighter check. In the local framework, however, the target lightens, because it is white at the highest luminance step (where it is the highest luminance) and superwhite at the surround step (where it is anchored to the dimmer checks defined as white). The final lightness of the target will be a weighted compromise between these two opposing tendencies.

Darkening due to superlocal grouping is expected to increase with checkerboard contrast (which would make lines slope upward). The reason is that the ratio of the patch to the highest luminance decreases (because the luminance of the brighter checks increases). However, lightening due to local grouping is also expected to increase with checkerboard contrast (which would make lines slope downward), the reason being that superwhite induction at the surround step increases (because the luminance of the dimmer checks decreases). The strength of the second force, and therefore the final balance, will depend on the weight given to luminance grouping, making for precarious settings. In Figure 2, smaller relative weights will yield values above the respective dashed lines, as is the case for more than half of the data points of Subject J.S. When the two conflicting forces cancel each other out, the result will be a roughly horizontal data line, as in the case of Subject I.B.

Conflicting Frameworks and Individual Differences

The specific predictions of the double-anchoring model, then, are the following. When it represents an increment relative to the luminances of the checks, a patch on checkerboard will look identical to an equal patch set on a uniform surround of the same space-averaged luminance. When it represents either a partial increment or a full decrement with respect to the checks, the patch on the checkerboard will appear darker. When it represents a partial decrement, it can appear lighter, darker, or even equal to the patch on the uniform surround, depending on how strongly it groups with the dimmer checks. It is important to note that the absolute magnitude of the effects discussed above depends on the relative weights of the various frameworks and of the two steps within each framework, but the direction of the effects does not. The only exception is the case of partial decrements, as we have seen; and, indeed, this is the only case in which the matches of different subjects depart appreciably from one another and display the largest variability.

Now, the strength of a framework is by definition a function of the number and type of grouping forces that keep its parts together (see Bressan, 2001). Frameworks created by "hard" grouping principles such as adjacency and good continuation, for example, tend to behave as stable entities and may be little affected by factors such as attention, experience, or the demands of the task. (It is virtually impossible to "ungroup" a square patch and its uniform background.) But in the case of partial decrements on an inhomogeneous surround, neither of the two alternative frameworks is stable. Superlocal grouping (with the checkerboard) is strengthened by adjacency but weakened by the conflicting contrast polarities. Local grouping (with the dimmer checks) is strengthened by luminance similarity but weakened by spatial arrangement (i.e., discouraged by the specific layout of T-junctions; see Figure 3). Such instability leaves room for interindividual differences (due to variations in attention, experience with the task, or interpretation of the task demands) and potentially also for intraindividual differences, in the form of variability across repetitions or sessions.

The two panels of Figure 2 illustrate this point nicely. Note that the data for the 2 subjects J.S. and I.B. are extremely similar in all conditions except for partial decrements. The measurements for the naive subject I.B. show neither darkening nor lightening, as we might expect under strong luminance grouping. I.B. consistently groups the patch with the dimmer checks. The measurements for the experienced subject J.S. show large variability and a tendency toward darkening (most values are above the respective dashed lines), as we might expect under weaker luminance grouping. In less neutral parlance, J.S. "counteracts" the tendency of the patch to group with the dimmer checks.

This hypothesis is of course purely speculative, but supporting evidence comes from a separate source (Melfi & Schirillo, 2000). In this work, the checkerboard was modified to produce T-junctions that favored the grouping of the patch with the dimmer checks, the brighter checks, or both. Three subjects participated in the experiment: Two were the inexperienced T.O.M. and D.L.H., and the 3rd was J.S. (here, J.A.S.), who had served as a subject in Schirillo and Shevell (1996). There were three checkerboards: the "original" (of the type depicted in Figure 1; this was the same as the checkerboard used by Schirillo & Shevell, 1996, and hence, the experiment was a replication of theirs); a "double-region" surround, in which both the brighter and the dimmer regions were adjacent to the test patch across the stem of the T-junction (see insets in Figure 4); and a "single-region" surround, in which either the brighter region alone or the dimmer region alone was adjacent to the test patch across the stem of the T-junction (see insets in Figure 5). Figures 4 and 5 plot the average percent difference between the test patch luminances set in the new experiment and in the original experiment (i.e., the replication of Schirillo & Shevell, 1996).

Double-region surround. This figure was designed so that the test patch would be affected equally by both the brighter and the dimmer regions. According to our hypothesis, grouping between test and surround regions will indeed be favored (because of the removal of T-junctions), but only on the basis of luminance similarity. For decrements, then, we expect stronger grouping of the patch with the dimmer region, not with both regions. The graph for decrements (Figure 4, bottom panel) shows that, indeed, for the 2 naive subjects the test patch looked lighter than it had in the original figure. This means that they grouped the decrements with the dimmer checks even more easily than they had in the original figure.

Interestingly, the measurements of J.A.S. are quite different from those of the other 2 subjects: His percent difference is always zero. As in the experiment of Schirillo and Shevell (1996), and unlike the other subjects, J.A.S. does not group with the dimmer checks when such grouping is demanded by luminance similarity, whether T-junctions work generically against grouping (as in Schirillo & Shevell, 1996) or are neutral (as in Melfi & Schirillo, 2000).

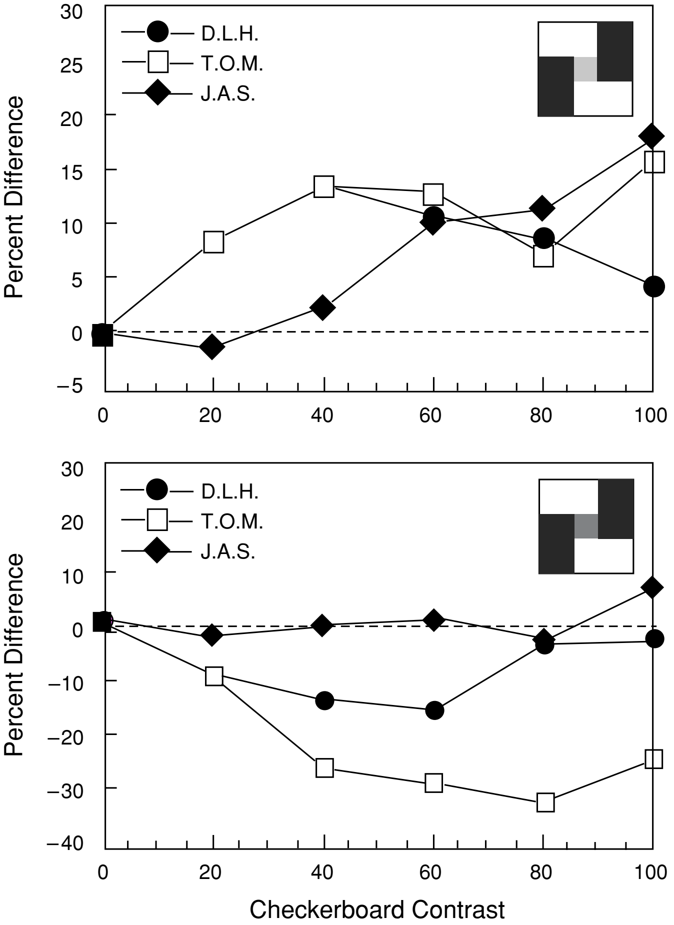

Figure 4. Percent difference between the brightness matches made on the double-region T-junction surround and those made on the original checkerboard surround for the 3 observers in the experiment of Melfi and Schirillo (2000). Values above the dashed lines indicate darkening, and values below the dashed line indicate lightening. Top panel: Increments. Bottom panel: Decrements. (From "T-Junctions in Inhomogeneous Surrounds," by T. O. Melfi and J. A. Schirillo, 2000, *Vision Research, 40*, p. 3739. Copyright 2000 by Elsevier. Redrawn after Figure 5 of Melfi & Schirillo, 2000.)

Consider now the graph for increments (Figure 4, top panel). On the basis of luminance similarity, here we expect stronger grouping of the patch with the brighter regions. Indeed, for all 3 subjects the test patch looked darker (8% on average) than it had in the original figure. J.A.S. shows this effect only for the final three data points—that is, he has a higher threshold than the other subjects.

Single-region surround. There were two versions of this display. The "light region T-junction" was designed so that the test patch would group preferably with the brighter region. For increments, luminance similarity also dictates grouping with the brighter region. The two forces work in the same direction, causing an additional darkening of the target of about 8% relative to the original figure (Figure 5, top left panel). J.A.S. groups with the brighter region as much as do the other subjects, when T-junctions push in that direction.

For decrements (Figure 5, bottom left panel), however, luminance similarity encourages grouping with the dimmer region, counteracting the influence of the T-junctions. The results are exemplary: The 3 subjects produce three completely different curves. T.O.M. shows obvious lightening—that is, he is more affected by luminance similarity (and groups the target with the dimmer checks) than by T-junctions. D.L.H. produces an unclear curve, showing slight lightening (effect of luminance similarity) in three cases and slight darkening in the other two (the rightmost two data points, where luminance similarity between test and dimmer region is lower due to the higher contrast between the two surround regions). J.A.S. shows obvious darkening—that is, he is more influenced by T-junctions than by luminance similarity. Again, J.A.S.'s judgments are not biased by luminance similarity grouping when this demands grouping with the dimmer regions.

The "dark region T-junction" was designed so that the test patch would group preferably with the dimmer region. For increments (Figure 5, top right panel), however, luminance similarity favors grouping with the brighter region, exactly as it did in the original figure. The flat data lines indicate no differences relative to the original figure: When opposed to the grouping cue of luminance similarity, the grouping cue of T-junctions has no effect. Incidentally, this implies that T-junctions, taken as *geometric* structures, are a totally inefficient grouping cue (Bressan, 2001). They work solely as *geophotometric* entities, playing a supporting role when contiguous surfaces have the right luminance relationships.

For decrements (Figure 5, bottom right panel), both luminance similarity and T-junctions support grouping with

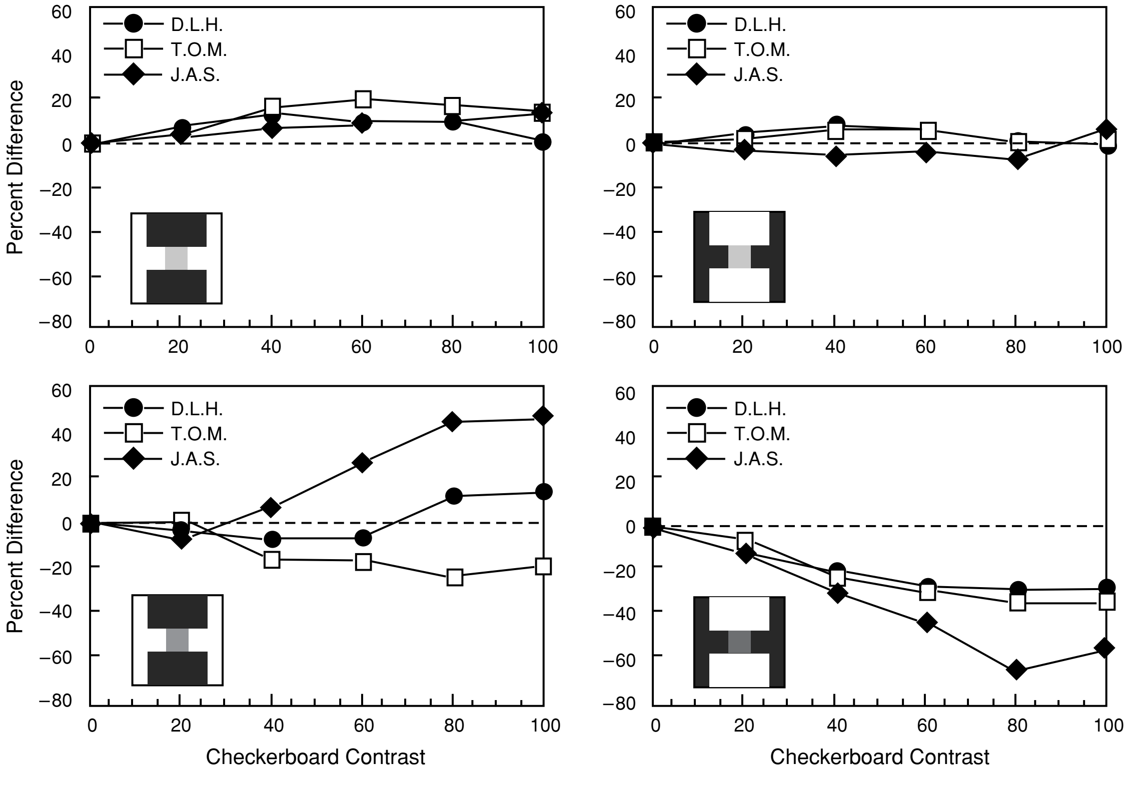

Figure 5. Percent difference between the brightness matches made on the single-region T-junction surround and those made on the original checkerboard surround for the 3 observers in the experiment of Melfi and Schirillo (2000). Values above the dashed lines indicate darkening, and values below the dashed lines indicate lightening. Top panels: Increments on a light region T-junction surround (left) and on a dark region T-junction surround (right). Bottom panels: Decrements on a light region T-junction surround (left) and on a dark region T-junction surround (right). (From "T-Junctions in Inhomogeneous Surrounds," by T. O. Melfi and J. A. Schirillo, 2000, *Vision Research, 40*, p. 3740. Copyright 2000 by Elsevier. Redrawn after Figure 6 of Melfi & Schirillo, 2000.)

the dimmer region. All 3 subjects show clear lightening (on average, 23% larger than that for the standard figure). This is the only occasion on which J.A.S. groups the test patch with the dimmer region, and he does so only because of the joint influence of T-junctions and luminance similarity.

Conclusions. The lightness of a patch on an inhomogeneous surround depends crucially on the groups that the patch forms with the contiguous surfaces and, therefore, on grouping cues such as good continuation and luminance similarity. If these grouping cues pull in opposite directions, individual differences emerge.

We have made this point by comparing the data patterns of Subjects T.O.M., D.L.H., and J.A.S. and noticing their remarkable regularities. When T-junctions work generically *against* grouping between the patch and its surrounding regions, as in the original checkerboard display, the lightness of partly incremental patches is nonetheless affected by grouping (with the brighter regions) via luminance similarity. When T-junctions are neutral, as in the double-region display, this bias becomes stronger—more so for some subjects (in the case at hand, T.O.M. and D.L.H.) than for others (J.A.S.). When T-junctions actually *favor* grouping between the patch and the brighter regions, as in the light single-region display, the bias also extends to J.A.S.

The same argument applies to patches that are partially decremental rather than partially incremental. When T-junctions work generically *against* grouping between the patch and its surrounding regions, as in the original checkerboard display, the lightness of partly decremental patches is nonetheless affected by grouping (with the dimmer regions) via luminance similarity. When T-junctions are neutral, as in the double-region display, this bias becomes appreciably stronger for some subjects (T.O.M. and D.L.H.) but not for others (J.A.S.). When T-junctions actually *favor* grouping between the patch and the dimmer regions, as in the dark single-region display, the bias extends to J.A.S.

Note that J.A.S. always clearly grouped according to T-junctions (cf. the two bottom panels in Figure 5): His curves are perfectly opposite and symmetrical. In contrast, when presented with the same displays, T.O.M. always clearly grouped according to luminance similarity: His curves have the same shape and direction.

FINAL REMARKS

Our discussion of the problem of equivalent backgrounds leads to two main conclusions. The first is that all the data make sense from a theoretical standpoint founded on anchoring principles. Accounts of lightness other than those based on anchoring can correctly predict that the target on the checkerboard will tend to darken. For example, one could assume that, by virtue of its higher luminance regions, a quadripartite field signals a higher level of illumination relative to a uniform region of the same average luminance. Hence, the target set on it would appear as a more illuminated, lower reflectance object than the companion target (see, e.g., Adelson, 2000; Lotto & Purves, 1999). However, there is at present no provision in these theories as to (1) why no appreciable darkening is found for fully incremental targets (whatever their absolute luminance may be); (2) why darkening increases with checkerboard contrast (which presumably signals increasing illumination levels) for partial increments but not for partial decrements; and (3) why significant individual differences emerge at all, and then only for partial decrements.

The second conclusion is that the existence of conflicting frameworks based on "soft" grouping cues gives free rein to individual variations in lightness assessment. Experiments on lightness are sometimes performed on very few subjects, often just 3 or 4. If individual differences such as those discussed here appear able to determine crucial fluctuations in the pattern of measurements, this becomes a problem—one of which theorists and data modelers should be well aware.

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NOTE

1. To be able to compare these data with those of Schirillo and Shevell (1996), who used two different luminances, I shall consider in this article only the results obtained by Bruno et al. (1997) with two-luminance surrounds (and with three-luminance surrounds for patches that were neither purely incremental nor purely decremental, for which no data were collected with two-luminance surrounds).

APPENDIX

Formal Rules of Double-Anchoring Theory of Lightness

In a simple image (one framework), such as a target on a uniform background that entirely fills the visual field, the final lightness value of the target is the weighted arithmetic mean of the values computed at the surround and highest luminance steps—that is,

$$L_{\mathrm{M}} = \left[\left(L_{\mathrm{t}} / L_{\mathrm{s}} \times W_{\mathrm{s}} + L_{\mathrm{t}} / L_{\mathrm{h}} \times W_{\mathrm{h}}\right) / \left(W_{\mathrm{s}} + W_{\mathrm{h}}\right)\right] \times L_{\mathrm{w}},$$

where L_{M} is the predicted matching luminance on white, L_{t} is the luminance of the target, L_{s} is the luminance of the surround, L_{h} is the highest luminance in the framework, L_{w} is the luminance of white, W_{s} is the weight of the surround step, and W_{h} is the weight of the highest luminance step. The weight of the surround step relative to that of the highest luminance step is a function of the surround's size (relative to the target), articulation, and absolute luminance.

In a scene containing two frameworks $f1$ and $f2$, such as a target on a uniform background that does not entirely fill the visual field, the final lightness of the target can be expressed as

$$L_{\mathrm{M}} = \left[\left(T_{f1} \times W_{f1} + T_{f2} \times W_{f2}\right) / \left(W_{f1} + W_{f2}\right)\right] \times L_{\mathrm{w}},$$

where W_{f1} and W_{f2} are the weights given to the two frameworks and T_{f1} and T_{f2} are the "territorial" lightnesses computed in the two frameworks. Each is determined by applying the equivalent of the previous equation without multiplication by L_{w}, which is done only once, at the final computation stage. The weight of a framework is a function first of its size, articulation, and absolute luminance, and second, of the number and type of grouping forces that make the target belong to it.

As a rule, we need to consider only two frameworks: the local and the peripheral framework. The local framework of a target consists of the target and its immediate surround. The peripheral framework consists of the target and the rest of the visual field. Frameworks are not normally nested; hence, the peripheral framework does not contain the luminance of the local surround. Only in cases of especially complex displays (such as targets set on checkerboards) do we need to take into account additional frameworks, intermediate between the local and the peripheral ones (such as a superlocal framework).

(Manuscript received December 12, 2003;
revision accepted for publication August 12, 2005.)