A common theoretical framework for brightness and lightness perception

In a review of the brightness/lightness literature, Kingdom (2011) noted that “Divided into different camps, each with its own preferred stimuli, methodology and theory, the study of LBT [lightness, brightness, transparency] is sometimes more reminiscent of the social sciences with its deep ideological divides than it is of the neurosciences” (page 652). Methodology and theory clearly separate our work from that of Gilchrist as described by Kingdom. The similarity of the underlying problems, however, has led us to investigate the roots of these differences and to propose a framework to bridge the divide and advance the field (Blakeslee & McCourt, 2015).

The common question for brightness/lightness research is: how, and under what circumstances, is the visual system able to differentiate the physically invariant reflectance of a surface from its potentially changing illumination? The visual system lacks direct access to either quantity, being given only their product which determines the retinal luminance (intensity) distribution. The recovery of surface reflectance and illumination is thus an inverse problem with no algorithmic solution, and observers must therefore employ knowledge or prior assumptions (conscious or unconscious, learned or innate) about these variables to approximate a solution.

We propose a framework for brightness/lightness research that resolves many of the confusions that have plagued communication between research groups (for details see Blakeslee & McCourt, 2015). The core ideas of this framework are that: (1) much of the confusion in the brightness/lightness literature stems from groups using different definitions of the central variables (brightness and lightness); (2) the term ‘lightness’, when defined simply as apparent reflectance, is underspecified with regard to illumination and is often used to refer to three independent and incomparable types of judgments. We discuss the above confusions and the false dichotomy between brightness and lightness research paradigms that they create, in relation to the preceding paper (Gilchrist, 2015).

(1) A false divide has been created by how the terms brightness and lightness are used and understood by different research groups

The Commission Internationale de l’Éclairage (CIE, 1970) defines the term brightness as the attribute of a visual sensation according to which a given visual stimulus appears to be more or less intense, or according to which the area in which a visual stimulus is presented appears to emit more or less light (Wyszecki, 1986; Wyszecki & Stiles, 1982). ‘Lightness’, on the other hand, is defined (CIE, 1970) as the attribute of a visual sensation according to which the area occupied by the visual stimulus appears to emit more or less light in proportion to that emitted by a similarly illuminated area perceived as a ‘white’ stimulus (Wyszecki, 1986; Wyszecki & Stiles, 1982). Although the CIE definitions are still widely used, it has become more common in visual psychophysics to use the definitions suggested by the Trieste group (Arend, 1993), who defined brightness as ‘apparent luminance’ and lightness as ‘apparent reflectance’.

While the CIE and Trieste group definitions of brightness appear very similar (luminance, after all, is a photometric measure of physical intensity), this term has come to be used quite differently by various research groups. Research groups (like ours), focused on the elucidation of early (ie ‘low-level’) visual mechanisms, are interested in brightness (apparent intensity) in general, and in brightness illusions in particular, because these phenomena are

† Gilchrist, A. (2015). Theoretical approaches to lightness and perception. Perception, 44, this issue.
thought to result from (and therefore reveal the nature of) early neural processes such as photoreceptor light adaptation, retinal and cortical luminance and contrast gain control, and spatial and temporal filtering by retinal, LGN, and early cortical receptive fields. To these groups of researchers, brightness refers to an appearance-based percept that is the outcome of significant early processing by the visual system.

Gilchrist (2006, 2015; Gilchrist et al., 1999), however, interprets the term ‘brightness’ (apparent luminance) to mean “the perception of a proximal quality—the raw intensity of some part of the image” (Gilchrist, 2006, page 6). Referring to the squares designated A and B (figure 1) in Adelson’s (1995) checkershadow illusion, Gilchrist (2015) writes in the preceding paper: “If we ask the question ‘Which of those two squares is brighter? What is the relative brightness of those two squares?’ That is a very difficult task. But lightness is not difficult” (page □□□).

What Gilchrist means here is clarified by his figure caption, which states “While it is easy to see the lightness of the squares marked A and B it is virtually impossible to appreciate that they are identical in luminance” (page □□□). Here, Gilchrist is equating brightness with physical intensity (ie luminance) rather than its perceptual correlate, which we acknowledge frequently differs from veridical luminance due to the significant early neural processing discussed above. Gilchrist (2015) devotes a large portion of the preceding paper to an attempt to equate the term ‘brightness’ with the perception of ‘raw sensations’, and proceeds to argue against the very existence of such sensations (and therefore presumably of brightness percepts generally). At one point he contends: “Now I have always wondered why there are any models of brightness, let alone many. Luminance is not informative … . It is very informative to know the reflectance of surfaces. … So it’s not clear to me why we have any theories of brightness at all” (page □□□). By equating ‘brightness’ with the raw (unprocessed) intensity distribution incident on the retina Gilchrist is grossly misrepresenting the term brightness as it is commonly used, and certainly as used by us. This creates a false viewpoint or divide and forms the basis for many of the arguments he advances in the current (Gilchrist, 2015) and earlier papers (Gilchrist, 2006; Gilchrist et al., 1999).

Confusion regarding the meaning of the term ‘lightness’, however, is even more serious and widespread than confusion about brightness. Recall that, because of the inverse problem, reflectance can only be estimated (correctly or incorrectly) based on knowledge or prior assumptions about illumination. The CIE (1970) defines lightness as perceived intensity relative to a similarly illuminated stimulus perceived as white. Although this resolves the
confound between reflectance and illumination under these conditions, it also means that the CIE definition may not pertain to stimulus conditions involving comparisons between shadowed and unshadowed regions. The definition of lightness as apparent reflectance (Arend, 1993), however, is also problematic because it ignores the inverse problem altogether by referring directly to a physical property of the stimulus (its reflectance) without any qualifications regarding illumination.

(2) Confusion has been created by the fact that lightness, defined simply as apparent reflectance, may refer to three very different types of judgments.

The data of Arend and Spehar (1993a, 1993b) and Blakeslee, Reetz, & McCourt (2008) provide experimental support for the idea that lightness, defined simply as apparent reflectance, may refer to three different types of judgments. These experiments demonstrate that under conditions of inhomogeneous illumination (e.g., where a target is in shadow, spotlight, or behind a transparency) observers can distinguish and match three independent dimensions of achromatic experience for that target: apparent intensity (brightness), apparent local intensity ratio (brightness-contrast), and apparent reflectance (lightness). Under homogeneous illumination, however, achromatic visual experience reduces to two dimensions where, depending on stimulus conditions and observer instructions, judgments of apparent reflectance (lightness) are either identical to judgments of apparent intensity (brightness), or to judgments of apparent local intensity ratio (brightness-contrast) (see also Rudd, 2010). The terms inferred-lightness (Blakeslee & McCourt, 2003; Blakeslee et al., 2008) and projective-lightness (Reeves, Amano, & Foster, 2008) have been introduced to distinguish lightness judgments where illumination inhomogeneities are taken into account. These lightness judgments are not directly based on the appearance of the target, but are instead estimates of how the target would appear without the shadow, spotlight, or transparency.

We have shown through careful review of past literature and by experiment that a failure to distinguish the basis for different types of lightness judgments is responsible for much of the current confusion and division in the field (Blakeslee & McCourt, 2012, 2015; Blakeslee et al., 2008). The three types of lightness judgments are in fact not comparable but are frequently unwittingly conflated due to the underspecified definition of lightness as simply ‘apparent reflectance’. This confusion is compounded by the inconsistent recognition by observers (and often by experimenters as well) of the type of information on which their lightness judgments are based, and of when an independent dimension of inferred-lightness is actually available (and therefore optimal) for matching (Blakeslee & McCourt, 2012, 2015; Blakeslee et al., 2008). For example, Gilchrist (2015) writes concerning lightness judgments in Adelson’s (1995) checkershadow illusion (figure 1), again referring to the squares designated A and B in the figure: “… lightness is not difficult. When you look at this, you see immediately that the lower square is a lighter shade of gray than the upper square” (page □□□). Here one must suppose that Gilchrist does not recognize that there is both a large brightness (apparent intensity) difference between the squares (an appearance effect) as well as an independent inferred-lightness (apparent reflectance) difference. In our view, what he claims you “see immediately” is the appearance-based brightness difference, not an inferred-lightness difference (Blakeslee & McCourt, 2012), and that referring to these appearance-based brightness judgments as lightness (apparent reflectance) judgments is misleading (and an incorrect usage of the term in this instance) because the presence of the visible shadow makes an independent inferred-lightness judgment of the squares beneath the shadow possible. This point is obvious if one examines the squares traversed by the shadow boundary in figure 1. Clearly, it does not make sense to argue that any one square has two lightnesses (apparent reflectances), but it certainly does have two brightnesses (apparent intensities), because illumination is non-uniform. Indeed, this is the textbook illustration of
the difference between brightness (apparent intensity) and lightness (apparent reflectance) (Palmer, 1999; Kingdom, 2011). We conclude that, in addition to resolving many of the confusions and paradoxes in the literature, the framework we suggest provides greater insight into the mechanisms the visual system employs to tackle the fundamental inverse problem of visual perception (Blakeslee & McCourt, 2015) under different conditions.

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The staircase Gelb stimulus
My question concerns the staircase Gelb stimulus. Like the original single-patch Gelb, it is a compelling and thought-provoking demonstration; but like the Gelb, is it not most simply explained in terms of contrast? Not wanting to sound like a broken record, but ‘contrast’ is not something that happens only at edges but involves the influence of distal regions. Each paper in the staircase will have a contrast to its neighbours, a contrast to the papers beyond its neighbours, and a contrast to the dark background. Because the dark background is so extensive, it will have a particularly strong contrasting influence on the papers, pushing their lightnesses into the upper part of the range and subjecting them to ‘gamut compression’.
Blakeslee, Reetz, and McCourt (2009) have made a comprehensive set of measurements of the brightness/lightnesses of the patches in a staircase Gelb (on a CRT), manipulating both the order of the squares as well as the luminance of the background. They found that the order of the squares influenced their relative brightnesses/lightnesses, contrary to predictions from the anchoring model, and that their multiscale filtering ODOG model gave an excellent account of the results. In anticipation of the rejoinder that in Gilchrist’s demonstration the staircase patches lie in a different depth plane to the background and are therefore only minimally influenced by it, this seems implausible. Suppose that the dark background filled the field of view and contained no features, like a Ganzfeld. I would predict that the lightnesses of the patches in the staircase would not be significantly altered as a result, but now there would be no information available as to the relative depth of the patches and background, so nothing to indicate that the two were not coplanar.

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Anchoring?
Some authors talk about a kind of anchoring in distance perception (He, Wu, Ooi, Yarbrough, & Wu, 2004). According to these authors, the visual system estimates distances by a surface integration process, which is based on surface slants. In this case, the nearest surface slant would be an anchor, based on which the visual system integrates, or not, further surfaces.
Having in mind the existence of this similar idea in distance perception, what do you think, or feel, about the application of the anchoring principles in other areas of perception? Can anchoring be one of the heuristics of human visual perception? Or even maybe one of the heuristics of perception in general?

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Reply to comments

Blakeslee and McCourt claim to offer a framework that “resolves many of the confusions that have plagued communication between research groups” (page [1] here). However, I believe that their claims actually add to the confusion.

“The common question for brightness/lightness research is: how, and under what circumstances, is the visual system able to differentiate the physically invariant reflectance of a surface from its potentially changing illumination?”

This is not the common question for brightness/lightness research. It is the question for lightness research, not brightness research. Brightness, by their own admission, is perceived luminance (‘apparent intensity’). Luminance is the product of both reflectance and illumination. There is nothing in either the CIE or Trieste Group definitions (Gilchrist, 1994, page 287) to suggest that brightness involves the disentanglement of reflectance and illumination. That is the challenge for lightness.

To say, as I do, that brightness is “the perception of a proximal quality—the raw intensity of some part of the image” (Gilchrist, 2006, page 6) is not to say, as Blakeslee and McCourt claim I do, that brightness is perfectly correlated with raw intensity. Likewise, to say that lightness is perceived reflectance does not imply that lightness is perfectly correlated with reflectance. To say that perceived size is the perception of size does not imply that perceived size is perfectly correlated with size.

Brightness is an experience that corresponds to luminance, and lightness is an experience that corresponds to reflectance. When a person makes a brightness match, they are instructed to choose a matching stimulus that is equal to a target stimulus in luminance. In other words, the task is to match a proximal quality. Failure to match it perfectly does not contradict the definition.

I do not equate brightness with physical intensity, as Blakeslee and McCourt claim. Rather, with conventional usage, I say that brightness corresponds to physical intensity. Physical intensity is the property that the subject is trying to match (and is instructed to match), however poorly they do that.

Blakeslee and McCourt claim that: “lightness, defined simply as apparent reflectance, may refer to three different types of judgments” (page [3] here) These are “apparent intensity (brightness), apparent local intensity ratio (brightness-contrast), and apparent reflectance (lightness)” (page [3] here).

These are not three uses of the term ‘lightness’. They are three different concepts, three different judgments, only one of which is lightness. Arend and Spehar (1993), to whom Blakeslee and McCourt attribute this three-part distinction, make it clear that the term ‘lightness’ refers only to apparent reflectance. I am not aware of anyone in the field who uses the term lightness for either ‘apparent intensity’ or ‘apparent local intensity ratio’. The only writers who conflate these terms appear to be Blakeslee and McCourt themselves.

Blakeslee and McCourt contend that, when visible illumination boundaries are present in the stimulus, lightness judgments are “estimates of how the target would appear without the shadow, spot-light, or transparency” (page [3] here). This is pure theory, not a statement of fact. When you look at the Adelson checkered shadow illusion, you see immediately that one target square is dark gray and the other is light gray. No cognitive inference is necessary. Work by Burkamp (1923) and Ingle (1985) implies that fish would see this stimulus just as humans do. Are the fish making an inference?

Blakeslee and McCourt assert that: “reflectance can be estimated (correctly or incorrectly) only based on knowledge or prior assumptions about illumination” (page [2] here). This is a theoretical claim and I disagree. There is information in the optic array that specifies reflectance, and we, like fish, have evolved circuits for extracting this.
These comments by Blakeslee and McCourt aptly illustrate my claim that there are no strictly low-level models of lightness, but that every low-level model includes a high-level component as well. Their low-level spatial filtering account is well known. But their invocation of ‘knowledge’ or prior assumptions” or “estimates of how the target would appear without the shadow, spot-light or transparency” (page [3] here) implies cognitive positions that I do not share.

Here Blakeslee and McCourt have aligned themselves with Hurvich and Jameson (1966, page 88), who wrote about the Hering spot-shadow demonstration:

In the situations described by Hering, the areas in question are perceived as lighter or darker—be they seen as spots or shadows—not because of our interpretations of the situation but because of the way the visual system happens to work as a physiological mechanism that responds to patterns of stimulation. It is the significance alone of the lighter and darker perceptions—whether the areas are perceived as properties of the surfaces or as properties of the illumination—that depends on our interpretation of the total situation.”

In other words, the contrast mechanism must be supplemented by cognitive interpretation.”

Let me make a final comment on the dependence of lightness on depth perception. My earlier findings (Gilchrist, 1977) that perceived spatial arrangements could cause a target to shift from black to white or vice versa with no change in the retinal image dealt a severe blow to the kind of low-level accounts from which the Blakeslee and McCourt ODOG model evolved. Low-level advocates at that time tried to claim that my data represented cognitive judgments and not genuine percepts of black and white. Generally, those same people have long since conceded the point, and today the view that lightness depends on depth perception is almost universally accepted.

Now, to my astonishment, Blakeslee and McCourt are trying to revive that early claim. And yet this should not be surprising. Unless they can successfully contend that lightness judgments in the presence of an illumination boundary are not based on appearance, the ODOG model is severely restricted in application; it would not be able to predict lightness matches in scenes that contain different depth planes. Look around you. How many scenes do not have different depth planes? 

Fred Kingdom asks whether all this cannot be simply explained by contrast. Despite its aura of concreteness, the term ‘contrast’ means all things to all people. Originally, contrast, as in lateral inhibition, was applied in point-wise fashion to every point in the visual field. Others saw it as an edge theory. But some people felt edge ratios were merely encoded, while others insisted the edge ratios were exaggerated. Some think the contrast at an edge has only a limited spatial range, leaving the problem of luminance scallops. Others use the contrast signal at the boundary to fill in the entire region within the boundary. And all these confusions arise merely from the simplest situation with two adjacent patches. Add a third region and the uncertainties multiply. Does that third region add to the inhibition acting on the first region, or does it reduce it through disinhibition? For a more detailed analysis of the many meanings of the term contrast, see pages 104–114 in Gilchrist (2006).

Presumably, Fred would agree that contrast, in its original meaning, was ruled out by my 1977 experiments on depth and lightness, which showed that manipulating perceived depth could push the lightness of a target almost from one end of the scale to the other, with no change in the retinal image and thus no change in the local contrast of the target. Now he offers a far more flexible definition of contrast that includes “a contrast to its neighbours, a contrast to the papers beyond its neighbours, and a contrast to the dark background” (page [5] here). Perhaps we can all agree that lightness is influenced by all of these relationships. But until the rules governing these interrelationships can be specified concretely, merely invoking the term ‘contrast’ will not be convincing. Kingdom writes that “‘contrast’ is not something that
happens only at edges but involves the influence of distal regions.” (page [5] here). Exactly how do distal regions influence local lightness? Does it make any difference whether the intervening edges are reflectance edges, illumination edges, occlusion boundaries, or corners?

Perhaps Fred has in mind multiscale spatial filtering, as in the ODOG model. That model does posit long-range contrast effects, but it would not be able to explain my earlier experiments on depth and lightness because the retinal image does not change. Given that almost every scene in the real world includes multiple, differentially illuminated planes, one might have thought that the discovery of a decisive role of depth on lightness would have dealt a fatal blow to the kind of structure-blind theories that, like ODOG, are tied to the retinal image. However, in an apparent attempt to rescue those theories, Blakeslee and McCourt (2015) now argue that the effect of depth in those experiments was not on vision per se, but on some cognitive estimate of what the lightness is likely to be.

Does Kingdom align himself with that claim? If so, that would explain why, in his 2011 *Vision Research* review, he did not include in his eight “major conceptual questions that engaged LBT researchers a quarter of a century ago” the question “Does lightness depend on depth?” I believe most people would regard that as a major conceptual question and one on which our knowledge has advanced.

But in a more charitable vein, Fred may be simply trying to cast anchoring theory in his favored contrast terminology. I argue that what have traditionally been called contrast effects can more usefully be understood in anchoring terms. Relative luminance values can be transformed into lightness values only when an anchoring rule is invoked. Contrast theories fail to specify any such rule, and thus they do not provide an output in terms of perceived reflectance values. Anchoring theory specifies a perceived reflectance value for each element within a framework of illumination—namely, target luminance divided by highest luminance, multiplied by 90%. In addition, of course, the influence of adjacent fields of illumination upon each other must be factored in. Anchoring theory attempts to quantify such influences. The current form of the theory may not be correct in all its details. I do agree that shuffling the five squares in the staircase Gelb display produces weak lightness effects that are not currently accounted for by that formula. But it is a good approximation. And the output is given in concrete reflectance values. Where is the contrast theory that predicts an outcome in terms of perceived reflectance?

Contrast theories fail to predict the magnitude of contrast effects. For example, when the familiar simultaneous lightness contrast pattern is embedded within a different context (Gilchrist et al., 1983), the perceived lightness difference between the two targets becomes six times greater! Merely invoking the “influence of distal regions” does not provide an adequate defense of contrast theories. Worse still, contrast theories fail to predict even the direction of effects in the many examples of reverse contrast (Agostini & Galmonte, 2002; Bressan, 2001; Economou, Zdravkovic, & Gilchrist, 2007; White, 1981).

Regarding the Blakeslee et al. CRT experiments, when the results of a CRT display differ from those obtained in the real world, what do you conclude—that your real-world percepts are mistaken? Obviously, those CRT displays do not look anything like the live staircase Gelb display. The CRT display does not have the same luminance range, it does not have the same resolution, and it does not create a compelling sense of depth. The surrounding context is severely restricted, and it simply does not look realistic. That hardly proves that ODOG can explain the staircase Gelb phenomenon.

**Oliver Tošković** asks whether anchoring is relevant to other perceptual dimensions than lightness. The short answer is yes. Generally, whenever perceived qualities depend on relationships, there is an anchoring problem. The best example is motion perception. It is likely that motion perception is based on the pickup of relative motion, not absolute motion
across the retina. This raises the obvious question of anchoring: which member of a stimulus pair expressing relative motion will be seen as stationary? Generally, the answer seems to be the larger of the two, or the one that surrounds the other.

An anchoring rule states a relationship between some perceptual value and some measure of the proximal stimulus. It is not immediately obvious why the perceptual value of the anchor in lightness should be white (although a good answer can be found in Brainard & Freeman, 1997). However, the perceptual value of the anchor in motion is highly intuitive: stationary.

Highly relevant in this regard is the classic chapter by Duncker (1929, 1950) on ‘induced motion’. Duncker specifically uses the term ‘anchor’. Moreover, fundamental to his analysis is the concept of frame of reference, just as in my anchoring theory.

With regard to space perception, the anchoring approach is very relevant to perceived size. For example, in some fields, like geology or paleontology, it is customary to place a ruler or other item of known size, in a photograph. Without that, the photograph readily shows the relative sizes of items but gives no sense of scale. This is the anchoring problem.

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