Gamut relativity: An innovative computational approach to visual surface perception

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Computational and Theoretical Neuroscience Lab

- One of four research areas within the Institute for Telecommunications Research

CTNL Lab

(www.itr.unisa.edu.au/ctnl)

Computational and Theoretical Neuroscience Lab

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- **PhD Students**: Daniel Padilla, Gao Xiao, Brett Schmerl, Siyi Wang

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Key current collaborators

- Prof. Lawrence Ward (Brain Research Centre, Uni. British Columbia, Canada)
- Assoc. Profs. John Bekkers and Christian Stricker (John Curtin School of Medical Research, ANU)
- Prof. Tony Burkitt and Assoc. Prof. David Grayden (Centre for Neural Engineering, Uni. Melbourne)
- Prof. Eric Schwartz (Center for Computational Neuroscience and Neural Technology, Boston University, USA)

Computational and Theoretical Neuroscience Lab

How does the brain compute, represent, communicate, learn and store behaviourally relevant information?

- Cortical computation, learning and representation (Vladusich/McDonnell/Schwartz; McDonnell/Bekkers/Schmerl)
- Hierarchical models of sequence learning (McDonnell/Brinkworth/Padilla)
- Modelling of stochastic neuronal/synaptic noise (McDonnell/Ward/Stricker/Zhou/Schmerl)
- Auditory neuroscience with applications in cochlear implants and biomimetic speech processing (McDonnell/Burkitt/Grayden/Xiao)

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Key recent publications

- **T. Vladusich.** (2013) Gamut relativity: A new computational approach to brightness and lightness perception. *Journal of Vision*, 13(1):14, 1-21
- **M. D. McDonnell** and L. M. Ward. (2011) The benefits of noise in neural systems: bridging theory and experiment. *Nature Reviews Neuroscience*, 12:415-426
- **M. D. McDonnell**, A. N. Burkitt, D. B. Grayden, H. Meffin and A. J. Grant. (2010) A channel model for inferring the optimal number of electrodes for future cochlear implants. *IEEE Transactions on Information Theory*, 56:928-940

My own strategic research approach

- **DARPA's Mathematical Challenge One**: "Develop a mathematical theory to build a functional model of the brain that is mathematically consistent and predictive rather than merely biologically inspired"
- **"Representation problem"**: What is the mathematical and/or computational form of the representations underlying perception and cognition?
- **"Computational theory and modelling"**: Focuses on the mathematical representations and operations that give rise to key perceptual phenomena (models not necessarily "neurally defined" but preferably "neurally relatable")
- **"Min. parameters, max. generality"**: Simplest theory/model that can explain several important phenomena (strategic goal to process arbitrary images)

Strategic research aims

- To develop a general, unified computational theory of visual surface perception, including surface "properties" such as lightness, transparency and gloss (**rapid recent progress**: Vladusich, 2012, 2013a-d)
- To design computational vision algorithms based on this theory to solve outstanding technological problems

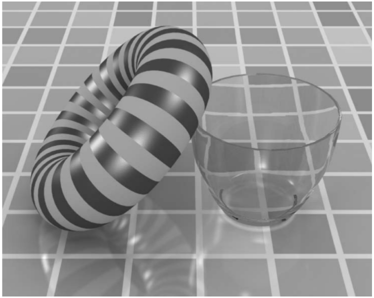


Figure from Todd *et al.* (2004)

Lightness and shadow

The checks labelled 'A' and 'B' share the same luminance yet appear to have different surface gray shades (**lightness** = perceived *diffuse* reflectance): *Lightness constancy* in shadow

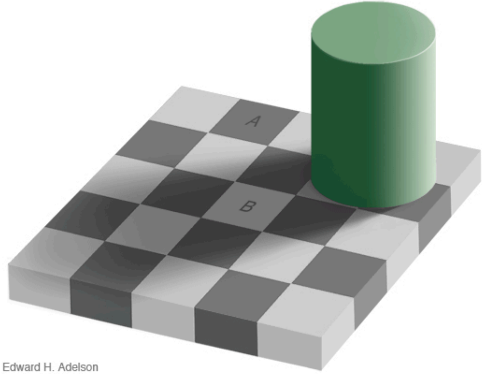


Figure after Adelson (1995)

Lightness and shadow

Unbelievers → Eliminating the surrounding context destroys the effect

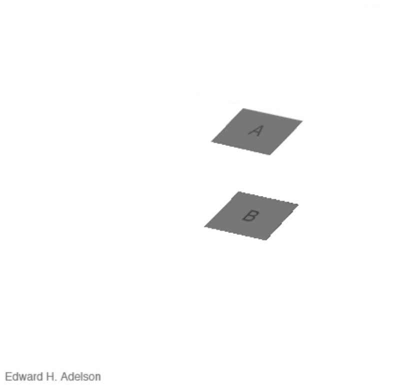


Figure after Adelson (2005)

Lightness and transparency

Physically identically circular textures are decomposed into black or white "moons" seen through partially transparent clouds (**transparency** = perceived transmittance): "scission" theory of lightness and transparency (Anderson, 1997, 2003)

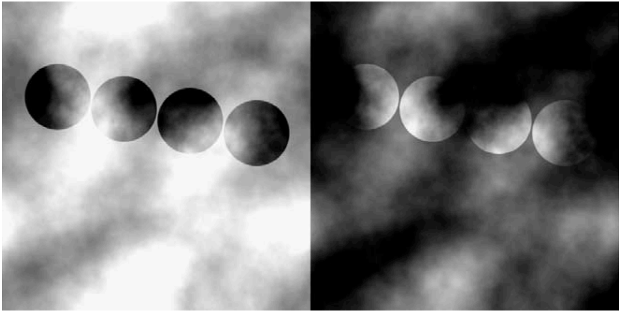


Figure from Anderson and Winnawer (2005)

Constraints on transparency perception

Unbelievers → Rotating the circular textures by 90 degrees with respect to the surrounding context destroys the effect: key geometric constraint must be met to perceive transparency

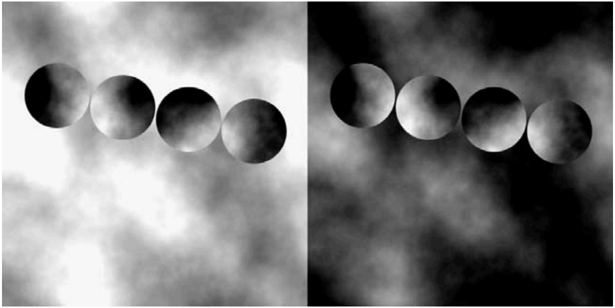


Figure from Anderson and Winnawer (2005)

Constraints on transparency perception

"Squares" on left and right are physically identical, but left is transparent and right is not: key luminance constraint must be met to perceive transparency

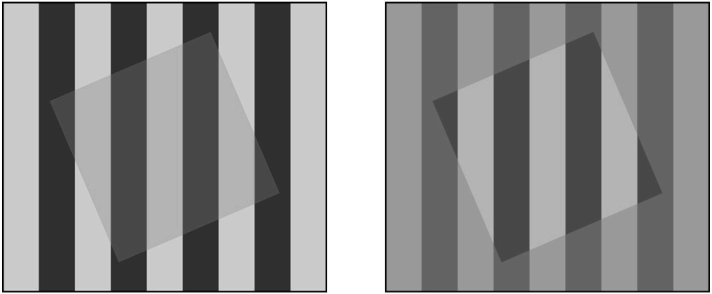


Figure from Fleming and Bülthoff (2005)

Lightness and gloss

These images have the same mean luminance but the right one looks glossier and blacker due to skewing of the luminance histogram (**gloss** = perceived *specular* reflectance)

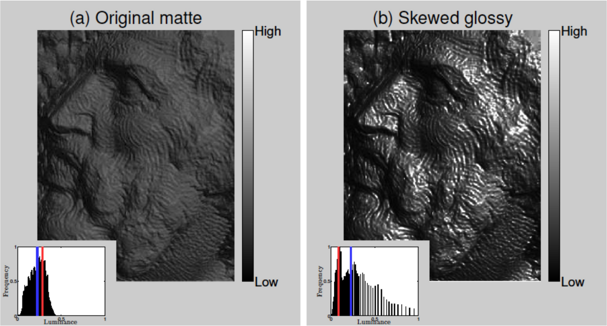
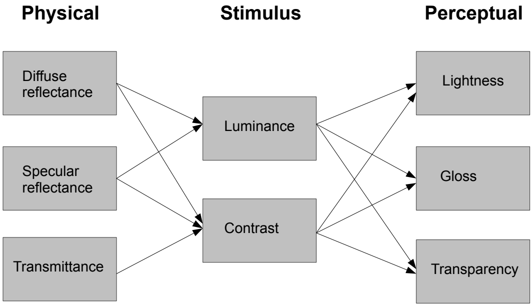


Figure from Vladusich (2013c), after Motoyoshi *et al.* (2007)

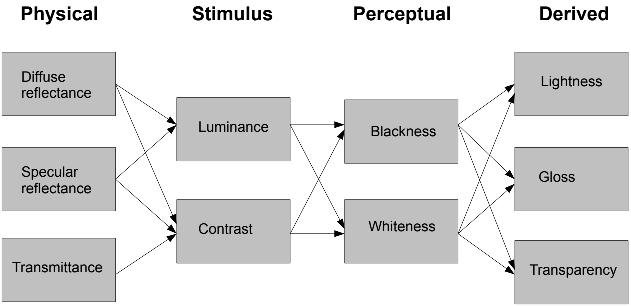
Dimensional mapping in classical theory

Physical dimensions map onto perceptual dimensions in a one-to-one manner (“reification”) (e.g. lightness = perceptual dimension corresponding to diffuse reflectance)



Dimensional mapping in gamut relativity

Perceptual dimensions are "constructed" by the visual system: Surface lightness, transparency and gloss properties derived naturally through the vector computation of surface and illumination layers in a perceptual "blackness-whiteness space"



Mathematical theory (simple "luminance" version)

Blackness
$$\phi = \omega_\phi \log \frac{k_\phi}{\ell} \tag{1}$$

Whiteness
$$\psi = \omega_\psi \log \frac{\ell}{k_\psi} \tag{2}$$

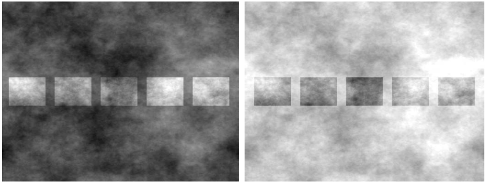
where ω_ϕ and ω_ψ are constants, $k_\psi \leq \ell \leq k_\phi$, giving $\mathbf{s} = \{\phi, \psi\}$

Mapping
$$\ell \to \mathbf{s} \to \mathbf{c}(\mathbf{s}) \tag{3}$$

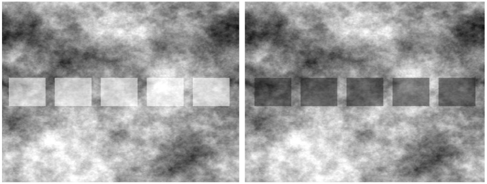
Luminance to "standard" to "comparison" achromatic colors

Transparency perception according to gamut relativity

Image decomposition into surface layers, one seen through another → Distinct types of vector computation in blackness-whiteness space (Vladusich, *J Opt Soc Am A*: 2013a)



Squares through clouds



Clouds through squares

Classical theory of transparency: α-blending

Metelli's α-blending approach

$$\ell_p = \alpha\ell_a + (1-\alpha)\ell_{pq} \tag{4}$$

$$\ell_q = \alpha\ell_b + (1-\alpha)\ell_{pq} \tag{5}$$

where $0 \leq \alpha \leq 1$

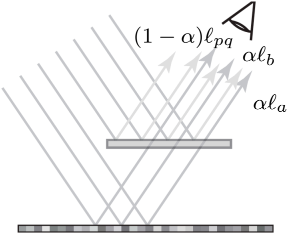


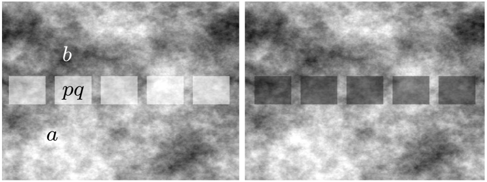
Figure from Fleming *et al.* (2011)

Classical theory of transparency: α-blending

Transmittance

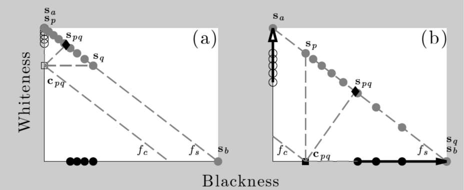
$$\alpha = \frac{\ell_p - \ell_q}{\ell_a - \ell_b} \tag{6}$$

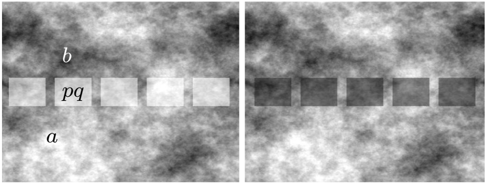
- where $\ell_b < \ell_q < \ell_p < \ell_a$ are the min. and max. luminance values in target and surround regions: these luminance constraints must be satisfied to perceive transparency
- α maps the physical dimension of transmittance to the perceptual dimension of transparency ("reification")



Gamut relativity: equivalent geometric approach

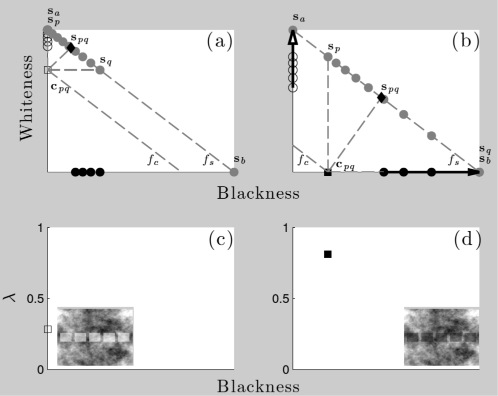
Foreground comparison color ($\mathbf{c}_{pq}$) computed at intersection of vertical and horizontal constraint lines given by whitest and blackest standard colors ($\mathbf{s}_p$ and $\mathbf{s}_q$) within each square region





Re-interpretation of transparency ("gamut relativity")

Lines f_s and f_c represent different **black-to-white (achromatic color) gamuts** with constant transparency level: normalised distance between comparison and standard gamuts



Definition of transparency

Definition of transparency in gamut relativity is equivalent to a logarithmic variant of the α-blending model: gamut lines of constant transparency rather than physical blending model

Transparency

$$\lambda = \frac{|\mathbf{s}_p - \mathbf{s}_q|}{|\mathbf{s}_a - \mathbf{s}_b|} = \frac{\log \ell_p - \log \ell_q}{\log \ell_a - \log \ell_b} \quad (7)$$

- $\lambda = 0$ when $\mathbf{s}_p = \mathbf{s}_q$ and $\lambda = 1$ when $|\mathbf{s}_p - \mathbf{s}_q| = |\mathbf{s}_a - \mathbf{s}_b|$

“λ-blending”

$$\log \ell_p = \lambda \log \ell_a + (1 - \lambda) \log \ell_{pq} \quad (8)$$

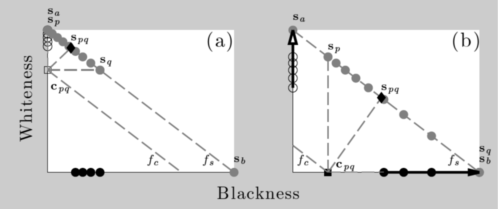
$$\log \ell_q = \lambda \log \ell_b + (1 - \lambda) \log \ell_{pq} \quad (9)$$

Duality theorem (“anti-reification theorem”)

Relates the definition of transparency in terms of distances between gamut lines to a definition based on distances along the standard gamut alone (see Vladusich, *J Opt Soc Am A*: 2013a, for a proof of the theorem)

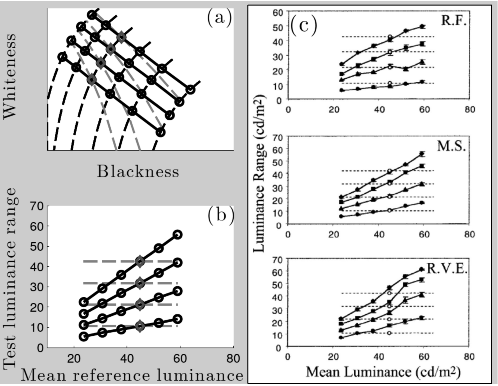
Duality theorem

$$\frac{|\mathbf{c}_{pq} - \mathbf{s}_{pq}|}{|\mathbf{c}_{ab} - \mathbf{s}_{ab}|} = \frac{|\mathbf{s}_{p} - \mathbf{s}_{q}|}{|\mathbf{s}_{a} - \mathbf{s}_{b}|} \qquad (10)$$



Gamut relativity *versus* α-blending

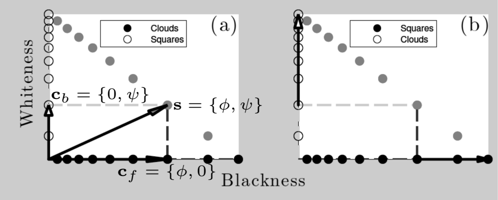
Gamut relativity explains a key asymmetry not explained by α-blending: Due to log compression, blackish layers look more transparent than whitish layers with the same transmittance (α)

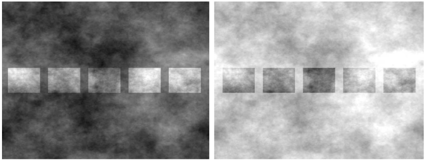


Data from Singh and Anderson (2002)

Transparency gradients and vector decomposition

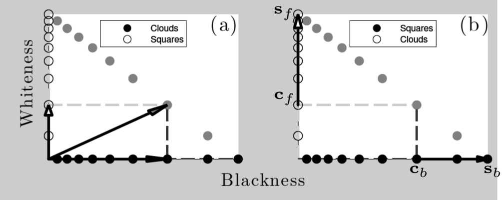
Gamut relativity also explains transparency gradients: standard colors ($\mathbf{s}$) are decomposed into pairs of vectors representing foreground ($\mathbf{c}_f$) and background ($\mathbf{c}_b$) comparison colors

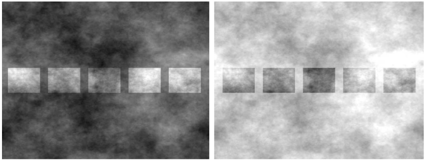




Computation of surface lightness

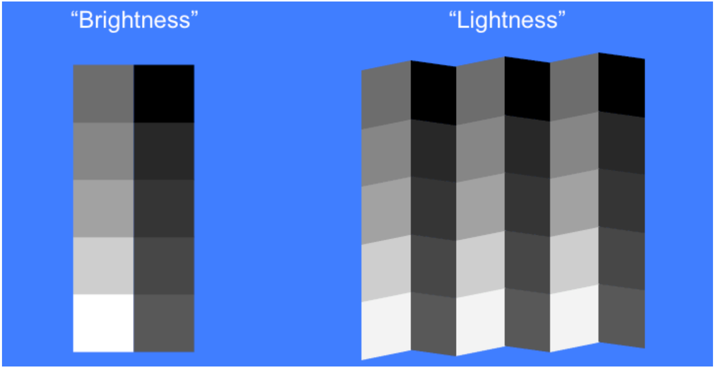
Comparison colors ($\mathbf{c}_f$,$\mathbf{c}_b$) are grouped by proximity in blackness-whiteness space to points seen in "plain view" ($\mathbf{s}_f$,$\mathbf{s}_b$) to form layered representations of black/white surface lightness





Lightness and brightness according to gamut relativity

Gamut relativity also accounts for the computation of lightness in shadows, re-interpreting lightness and brightness (perceived luminance) as computationally defined "modes" rather than perceptual dimensions of vision (Vladusich, *J Vis*: 2013)

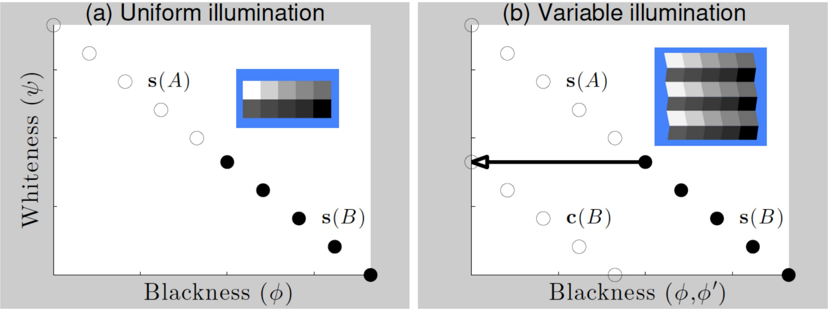


A simple model of diffuse surface reflections

- Image luminance values, $\{\ell_{10}, \ell_9 ... \ell_1\}$, ranked in descending order
- $A = \{\ell_{10}, \ell_9, ..., \ell_6\}$ and $B = \{\ell_5, \ell_4, ..., \ell_1\}$, where $B = kA$, with $k < 1$
- $A = I_A R_A$ and $B = I_B R_B$, where I_A and I_B are illumination intensities; $R_A = \{\rho_{10}, \rho_9, ..., \rho_6\}$ and $R_B = \{\rho_5, \rho_4, ..., \rho_1\}$ are diffuse reflectance sets
- **Extreme cases**: Uniform illumination ($I_A = I_B$) and different reflectance sets ($R_A \neq R_B$), or identical reflectance sets ($R_A = R_B$) and variable illumination ($I_A \neq I_B$)
- Any linear combination of these extreme cases possible!

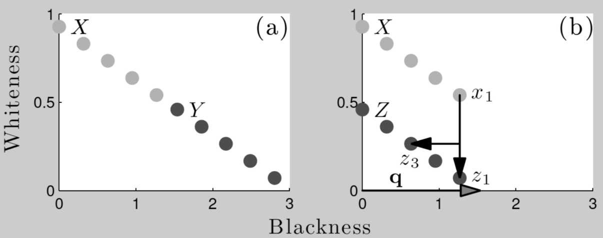
Brightness and lightness “modes” in gamut relativity

Given image cues favouring either **uniform** illumination over **planar** surfaces or **variable** illumination over **corrugated** surfaces, blackness co-ordinates correlated to variations in either luminance (“brightness”) or diffuse reflectance (“lightness”)



Grouping into surface lightness layers

"Lightness constancy": comparison colors "grouped" to standard colors; blackness-whiteness asymmetry ($\omega_\phi > \omega_\psi$) and "correspondence theorem" explains many otherwise puzzling perceptual data that contradict classical theory (Vladusich, *Vision Res*: 2012, *J Vis*: 2013, *Color Res Appl*: 2013, in press)



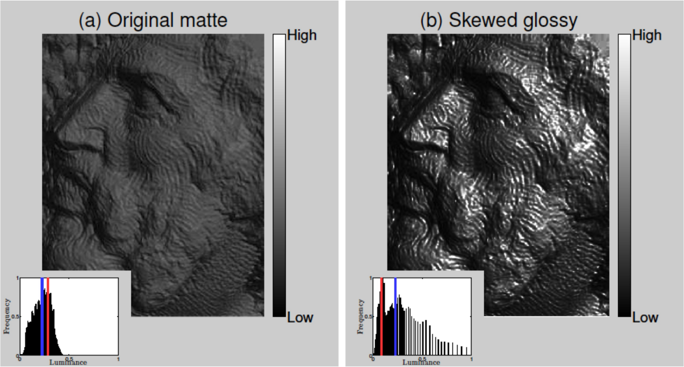
"Balancing" the brightness/lightness modes

$$\mathbf{c}\,(B) = \mathbf{s}\,(B) - \Omega\mathbf{q} \tag{11}$$

- where $\mathbf{q} = \{\phi(\ell_5) - \phi(\ell_{10}), 0\}$ is the projection vector—onto the blackness axis—formed between the whitest standard colors in sets A and B (i.e. associated with the highest luminance value in each set)
- $0 \leq \Omega \leq 1$ is an "anchoring/scission" parameter, computed in an unknown manner from both bottom-up cues and top-down biases
- Ω determines the balance between brightness and lightness modes (defines the linear mixture of uniform- and variable-illumination extremes)

Gloss perception according to gamut relativity

Gamut relativity re-interprets gloss perception in terms of a generalised scheme for the vector computation of surface and illumination properties (Vladusich, *J Opt Soc Am A*: 2013b, in press)

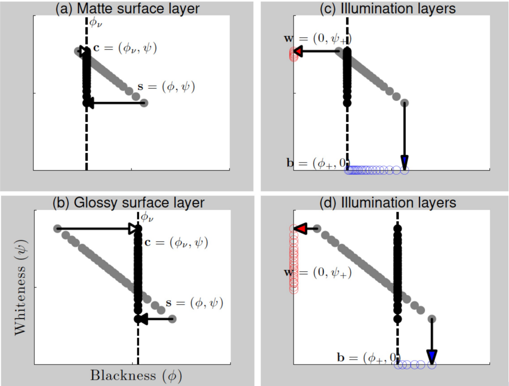


Lightness constancy, highlights and gloss

- **Problem**: Surfaces with high specularity (e.g. “highlights”): highest luminance not indicative of diffuse reflection, so cannot “anchor” blackness on these values (Vladusich, *J Opt Soc Am A*: 2013b, in press)
- **Solution**: Generalise vector computation of blackness co-ordinates to better correlate with diffuse reflection: use simple model of diffuse/specular reflections, under assumption of spatially uniform diffuse reflectance
- Diffuse reflection → mode luminance (ℓ_ν) → mode standard color ($\mathbf{s}_\nu$) (seen in “plain view”)
- Specular reflection → max. luminance (ℓ_+) → max. standard color ($\mathbf{s}_+$) (“highlights”)
- **Outcome**: First unified account of surface gloss/lightness (e.g. lightness constancy in presence of highlights)

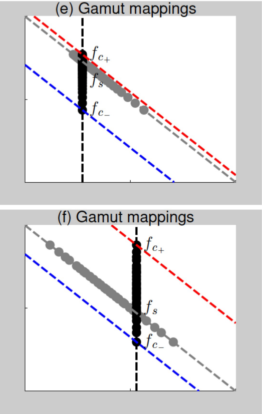
Computation of surface and illumination layers

Vector shifts towards the “mode” standard color (associated with most frequent image pixel) produce matte or glossy surface lightness layers, whereas vector shifts towards the axes produce “whitish” highlight and “blackish” shading/shadow layers



Surface gloss understood as “gamut relativity”

Gloss level given by distance between standard and comparison gamut lines (f_s and f_{c+}) *above* the standard gamut (distances *below* represent transparency level of the shadow/shading layer)



Duality theorem: redux

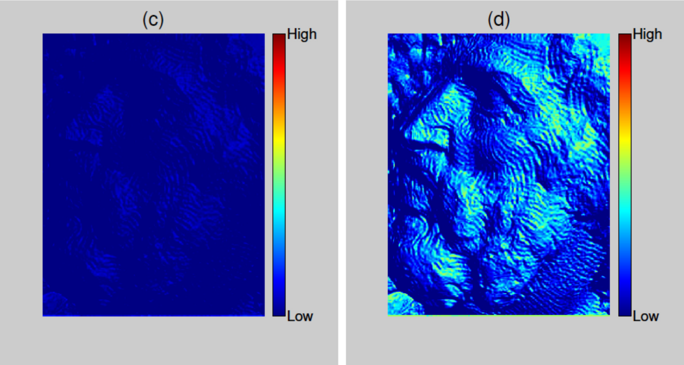
Duality theorem now relates the definition of *gloss* in terms of distances between gamut lines to a definition based on distances along the standard gamut alone: Using this relation we can compute gloss according to

$$\lambda_+ = \frac{|\mathbf{s}_+ - \mathbf{s}_\nu|}{|\mathbf{s}_b - \mathbf{s}_w|} \tag{12}$$

- where $\mathbf{s}_+$ and $\mathbf{s}_\nu$ represent highlight and mode colors lying on the standard gamut line
- and $\mathbf{s}_w$ and $\mathbf{s}_b$ represent the white and black endpoints of the standard gamut line
- gloss level (λ_+) ranges from 0 when $\mathbf{s}_+ = \mathbf{s}_\nu$ to 1 when $|\mathbf{s}_+ - \mathbf{s}_\nu| = |\mathbf{s}_w - \mathbf{s}_b|$.

Surface gloss predictions

The theory makes quantitative predictions of surface gloss level at any given image location, given the luminance of the surface region appearing in “plain view”: these predictions can be easily tested in perceptual experiments



Relationship to previous work

- Vector computation of layered representations in blackness-whiteness space unifies extant concepts of lightness "anchoring" (Gilchrist, 1999), "scission" (Anderson, 1997, 2003) and "atmospheres" (Adelson, 2000)
- Layered representation (Anderson, 2011) without "reified" physical dimensions or impossible "inverse optics" computations (Motoyoshi et al., 2007)
- New approach to perceptual grouping (Gilchrist, 2006): computation of surface layers by proximity in blackness-whiteness space
- Gamut relativity clarifies previous attempts to understand visual surface perception in terms of ON and OFF channel activity levels (Motoyoshi et al., 2007): Blackness $\rightarrow$ OFF, whiteness $\rightarrow$ ON

Implications

- Blackness co-ordinates don't themselves black-to-white gamuts: "gamut relativity" undermines the assumption of an "absolute" gamut (or lightness dimension)
- Idea of brightness and lightness "modes" fits better with the known properties of the brain ("dynamic states") than the idea of brightness and lightness dimensions
- Balance between these modes can be psychophysically altered by modulating bottom-up cues and top-down biases in a predictable way (Ω)
- First unified computational theory of brightness, lightness, transparency and gloss perception: mathematical tools applied to one domain are now applicable to the others

Conclusions

- No "explicit" computation of brightness, lightness, gloss and transparency: Perceptual properties arise naturally from vector computation of surface and illumination layers in blackness-whiteness space ("antidote to reification")
- Local luminance plays the predominant role, with local contrast playing only a supporting role in specifying blackness-whiteness co-ordinates (Vladusich, *J Vis*: 2013)
- Predicts differential roles for neural ON and OFF channels in visual surface perception, and suggests new design ideas for engineered vision systems
- Gamut relativity unifies and clarifies the study of visual surface perception, makes a host of testable predictions, and generally opens up a vista of novel research avenues