Welcome to Today’s Webinar!

COLOR CONSTANCY – SEEING COLOR IN A CHANGING WORLD

21 June 2021 • 10:00 EDT (UTC -4:00)
Technical Group Executive Committee

Francisco Imai
Chair of the OSA Color Technical Group

Rigmor C. Baraas
University of South-Eastern Norway

Javier Hernandez-Andres
Universidad de Granada

Manuel Spitschan
University of Oxford
About the Color Technical Group

Our technical group focuses on all aspects related to the physics, physiology, and psychology of color in biological and machine vision.

Our mission is to connect the 900+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

• Workshop on Color Imaging, Perception and Reproduction @ CIE 2019 Session
• Incubator Meeting on Visual Perception in AR/VR with Display Technology TG
• Webinars, Data Blitz
• Bi-Weekly Coffee Breaks
Connect with our Technical Group

Join our online community to stay up to date on our group’s activities. You also can share your ideas for technical group events or let us know if you’re interested in presenting your research.

Ways to connect with us:

• Our website at www.osa.org/vc
• On Twitter at #OSAColorTG
• On LinkedIn at www.linkedin.com/groups/13573604
• Email us at TGactivities@osa.org
Next Color Technical Group Webinar!

THE DEVELOPMENT OF COLOR PERCEPTION

13 July 2021 • 10:00 EDT (UTC -4:00)
COLOR CONSTANCY – SEEING COLOR IN A CHANGING WORLD

21 June 2021 • 10:00 EDT (UTC -4:00)
Today’s Speaker

Maria Olkkonen
Durham University & University of Helsinki

Short Bio:
• Graduated from psychology at the University of Helsinki in 2004
• Work as research scientist at Nokia Research Center in 2005
• Ph.D. Project in color constancy at Karl Gegenfurtner’s Lab in Giessen in 2009
• Post-doc:
  • David Brainard’s lab at UPenn on Material Perception
  • Prof. Sarah Allred at Rutgers on Color Perception
  • Prof. Russel Epstein at UPenn on fMRI project
• Assistant Professor at Durham University in 2015 and started lab at University of Helsinki
Color Constancy – Seeing Color in a Changing World

Dr. Maria Olkkonen
Department of Psychology and Logopedics, Faculty of Medicine, University of Helsinki
Department of Psychology, Durham University

Ellen Thesleff: Lehtimaja (1908)
Some benefits of (trichromatic) color vision

Where are the fruit?

Which fruit would you eat?

Which face looks healthier?

Color manipulation by Tarja Peromaa
Original image: Samuelsson et al (2012), J Med Internet Res, reprinted with permission from P Carlbring
Outline for today

• What is color constancy? Why is it an information processing challenge?

• How can color constancy be measured in the laboratory?

• Which color constancy mechanisms have been suggested? What is the experimental evidence?

• The development of color constancy

• Summary and open questions
Perceiving surface color in natural environments

• When we speak about color, we usually mean surface color (e.g. the redness of the tomato, the particular shade of green of our walls)

• If the illumination were always the same, and we viewed objects in the same context, color perception would be relatively straightforward

• Alas, illumination varies naturally due to time of day and weather, and due to different artificial light sources

• Same goes for viewing context
Color appearance depends on context

Purves & Lotto, 2002
Color appearance depends on context

Purves & Lotto, 2002
Color constancy: challenge for color perception
Illumination variation

- **Direct sunlight**: Most power in long wavelengths
- **Average daylight**: Most power in short-medium wavelengths
- **Skylight**: Most power in short wavelengths
- **LED lamp**: Relative power distribution
- **Halogen lamp**: Relative power distribution
Interaction between illumination and reflectance

Surface property: reflectance

Illumination

Reflected light

Reflectance

Wavelength (nm)

Relative power

Skylight

Sunlight

LED

Wavelength (nm)

Relative power

Skylight

Sunlight

LED

Wavelength (nm)

Relative power

Skylight

Sunlight

LED

Wavelength (nm)
The problem: how do we know what the surface color is when the sensory signal varies?

• There is no 1-1 correspondence between sensory signal and external object property —> underdetermined computational problem

• How does the brain solve this problem?
Possible computational mechanisms

• *Image-based solutions*: cues in the image (visual scene) are used to either implicitly or explicitly estimate the illumination and by discounting it, estimate surface reflectance

• *Probabilistic models*: in this approach, sensory information is combined with prior knowledge, gathered over several exposures to visual scenes, to estimate the illumination/surface reflectance
Suggested solutions: image cues*

- Local contrast (e.g. Valberg & Lange-Malecki, 1990)
- Gray world hypothesis (e.g. Buchsbaum, 1980)
- Brightest is white (e.g. Hurlbert, 1998)
- Chromaticity convergence, or using highlights to estimate the illumination (e.g. Lee, 1986)

*not a comprehensive list
Suggested solutions: image cues

- **Local contrast**: (e.g. Valberg & Lange-Malecki, 1990): if the surround of the object is constant and the illumination change is spatially uniform, the color ratio between the object and the surround will stay constant under illumination changes

  - Caveat 1: There is no guarantee that the illumination change is spatially uniform

  - Caveat 2: The assumption that the surround of the object remains stable is only true in static scenes, and the visual system can clearly estimate surface color in dynamic scenes
Suggested solutions: image cues

• **Gray world hypothesis** (e.g. Buchsbaum, 1980): if the world is on average gray, any color bias in the image indicates a chromatic illumination. Illumination can be estimated and discounted by taking the average color over the scene.

  • Caveat 1: if the gray world assumption is wrong and the scene is in fact not gray on average, this approach will fail

  • Caveat 2: this is clearly not what the visual system is doing, because we do see illumination differences between scenes. The brain is not “white balancing”, at least not fully.
Suggested solutions: image cues

• “Brightest is white” (e.g. Hurlbert, 1998): the assumption that the brightest surface in the scene is white, i.e. has a flat reflectance. We can use this surface to “measure” the illumination chromaticity, a bit like using a white standard surface in camera calibration

  • Caveat 1: This only works if there is actually a white surface in the scene, which is not always the case

  • Caveat 2: this is clearly not the only cue to color constancy, because our visual system does just fine even without white surfaces in sight
Suggested solutions: image cues

- **Illumination chromaticity from highlights on glossy surfaces**: glossy surfaces reflect part of the illumination back to the viewer, which is visible as highlights. It is possible to estimate the illumination chromaticity from highlights across a few glossy objects (Lee, 1986; Hurlbert, 1998)

  - This is indeed a good cue because there are usually always some glossy surfaces in sight (the surfaces don’t have to have mirror reflections for chromaticity convergence to work)

  - But it is unclear whether this cue is actually used by the human visual system (but see Wedge-Roberts et al, 2020)
Suggested solutions: probabilistic approaches

• Another type of approach emphasizes learning statistical regularities from lots of images and applying this knowledge to estimate surface reflectance.

• This approach is implemented in probabilistic (e.g. Bayesian) models.

• Prior knowledge is represented in these models as prior probability distributions, e.g. over possible illumination chromaticities.

• The final surface color estimate is akin to a weighted average of noisy sensory information and prior knowledge.
Pros and cons of probabilistic models

• These models incorporate the reasonable assumption that previous knowledge affects perception (cf. von Helmholtz and others)

• They take into account the fact that sensory information processing is noisy and allow modeling the effects of noise on the percept

• They have been criticized for being too flexible, i.e. “one can model anything with probabilistic models”. This caveat can be overcome with careful choice of model parameters and careful experimental validation of the models
What do experiments tell us about which cues and strategies observers use in color constancy tasks?
What do experiments tell us about which cues and strategies observers use in color constancy tasks?

How is color constancy measured in the laboratory?

Traditional matching methods

- All of these methods have in common the manipulation of real or simulated illumination over space or time.
  - Achromatic adjustment: adjust a patch in a scene to appear achromatic (gray); repeated across two or more illuminations.
  - Asymmetric matching: adjust test patch under illuminant B to match reference patch under illuminant A in terms of color appearance.
Quantifying color constancy

- Neutral illuminant
- Test illuminant
Quantifying color constancy

CCI = 1 - ||a|| / ||b||

CCI = 0 → no constancy
CCI = 1 → full constancy
Performance-based methods: object selection/identification

Zaidi & Bostic (2008): Which is the odd-one out?

Radonjic et al (2015): Which blocks in the source match the ones in the model?

Wedge-Roberts et al (under review): Which sweet in B matches the sweet in A?
Matching vs. object selection

• Most color constancy data have been collected with matching methods. Because matching is arguably unnatural, it may lead to differences in observer strategies, resulting in highly variable data.

• Performance-based methods are increasingly used because they better resemble real-life color tasks, and thus may lead to less variability in observer strategies and performance.

• Performance-based methods are also possibly easier for children in developmental studies.
What do experiments tell us about which cues and strategies observers use in color constancy tasks?
Kraft & Brainard (1999)

• Question: which cues are observers using to estimate surface color: local contrast, global mean (“gray world”), “brightest is white”?

• Task: adjust the test patch until it looks achromatic (gray)

• Kraft & Brainard separately silenced the cues of local contrast, global mean, and brightest surface one by one and measured color constancy

• If any of those cues determined color constancy, performance should drop to near zero when that cue was silenced
Kraft & Brainard (1999): manipulations

**Local contrast cue** was silenced by changing the background from A to B so that across the illumination change, the local contrast between background and test patch remained constant.

**Global mean cue** was silenced by changing the background from A to B so that across the illumination change, the global mean chromaticity was constant.

**Brightest surface cue** was silenced by changing the local surround of the test patch across the illumination change as to keep its chromaticity constant.
Kraft & Brainard (1999): results

- Color constancy did not drop to zero in any condition, even if all the cues were removed.
- There must be other cues that observers are using even in the most impoverished scene.
Other cues?

- *Mutual illumination*: incoming light reflects off surfaces multiple times —> with several bounces between surfaces, the reflected light contains information about the illumination which can be used to estimate the illumination (Funt et al, 1991; Hurlbert, 1998)

- *Highlights*: it is possible to estimate the illumination chromaticity from specular highlights (Lee, 1986; Hurlbert, 1998)
Are highlights used to estimate surface color?

- Wedge-Roberts et al (2020) empirically tested whether human observers use the highlight/chromaticity convergence cue
- Color constancy was measured with achromatic adjustment in scenes with either matte or glossy objects

- The chromaticities of glossy surfaces fall between the “body color” and the illumination color
- With more than one glossy surface, the illumination can be estimated by looking at the convergence point of the color values
Are highlights used to estimate surface color? Wedge-Roberts et al (2020)
Are highlights used to estimate surface color? Wedge-Roberts et al (2020)

- Yes, when other strong cues are weakened (i.e. removing the white background in Experiment 1)
- The effect is small, but can be relevant when there are few other cues to the illuminant

Also see Yang & Maloney, 2001; Yang & Shevell, 2002; Lee & Smithson, 2016
Probabilistic color constancy: natural illumination statistics

- Outdoor illuminations have much more variation in the blue-yellow direction of color space than in the orthogonal direction.
- The variation follows a curve in color space called the daylight locus.
- Does the visual system use this as a constraint when estimating surface color?

Spitschan et al, 2016
Does color constancy incorporate the statistical regularity of natural daylight? Delahunt & Brainard (2004)

- Illuminations sampled from the daylight locus (blue/yellow) and from the orthogonal direction (red/green)
- Achromatic adjustment task in rendered 3D scenes
- Constancy was best for blue and green illuminations —> partial evidence for a daylight prior
Does the visual system use a daylight prior?


- A broad prior centered on the average daylight chromaticity gave the best fit to the observed data
Does the visual system use a daylight prior?

• Color constancy tends to be best for bluish daylight illuminants, but NOT for yellow daylight illuminants

• In other words, the visual system does not seem to use a narrow, symmetric daylight prior to estimate surface reflectances, but possibly a broader or asymmetric one
Interim summary

- Constancy is a hard problem for the visual system, which it nevertheless seems to solve quite well in everyday life (we are usually able to pick those ripe bananas or tomatoes).

- In laboratory conditions, constancy varies between quite poor (close to 0) and very good (close to 1).

- Laboratory studies have elucidated the cues and strategies that the visual system uses to achieve color constancy, although much remains unknown.
Development of color constancy
Color constancy in childhood

• Infants have rudimentary color constancy by 4.5 months (i.e. they can to some extent separate reflectance changes from changes in reflected light; Dannemiller & Hanko, 1987; Dannemiller, 1989; Yang et al, 2013, 2015)

• 2-4 year toddlers show some color constancy, with the level of color constancy correlating with color naming ability (Rogers et al, 2020)

• What about developmental trajectory beyond 4 years?
Developmental trajectory of color constancy

• We asked how color constancy develops from 6 to 11 years and how performance in this age range compares to adults

• Two daylight illuminants (blue/yellow), two orthogonal illuminations (red/green)

• Child-friendly task: pick Derek the dragon’s favorite sweet
Task: Feed Derek the Dragon his favorite sweet from the options on the right.
Target

Tristimulus match (T)
Reflectance match (R)

1 2 3 4
5 6 7 8

u* v*
Results: children show better color constancy

- Overall, color constancy indices were **higher** for children than for adults (Exp 1: 0.44 vs 0.36***; Exp 2: 0.32 vs 0.25***)

- In both age groups, constancy was best for the blue illumination, consistent with Delahunt & Brainard (2004)
There was a linear decrease in the constancy index for children with age for all illuminations.

No relationship for adults.

Similar results for 2D and 3D.
Summary

• Children surprisingly show *better* constancy than adults

• This could be due to different strategies - perhaps adults are trying to make a tristimulus or appearance match, which leads to lower color constancy indices. This needs to be investigated further with systematic manipulation of scenes and instructions, and by measuring eye movements

• Evidence of a “bluish” daylight prior in both age groups, broadly in line with Brainard et al (2006) and Pearce et al (2015)

• Similar pattern of constancy over surface reflectance and illumination for both age groups
Open questions

• What we know…
  • Human observers use multiple cues to estimate surface color; no one cue is sufficient or necessary
  • These cues vary from low-level (e.g. local contrast) to more complex (e.g. highlights, scene geometry generally)
  • Ability to use some cues develops very early, around 4 months, and color constancy (at least in relatively simple scenes) is remarkably good by 6-11 years
  • There is large variability in color constancy across individuals, perhaps related to attention and cognitive strategies

• What we don’t yet understand fully…
  • What exactly causes the large variability between individuals in laboratory tasks
  • Why does constancy in the laboratory decrease from school children to adults
  • What is the relative importance between image cues and prior knowledge
  • Neural mechanisms of constancy
We are making progress…

Questions?

maria.olkkonen@helsinki.fi