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Checklist for Daltonization methods: Requirements and characteristics of a good recolouring method

Joschua Simon-Liedtke*, David R. Flatla** and Eskild Narum Bakken; *The Norwegian Colour and Visual Computing Laboratory, Faculty of Computer Science and Media Technology, Norwegian University of Science and Technology (NTNU), Gjøvik, Norway.; **Computing, School of Science and Engineering, University of Dundee, Scotland; ***Faculty of Technology, Economy and Management, Norwegian University of Science and Technology (NTNU), Gjøvik, Norway.***

Abstract

People with Colour Vision Deficiencies (CVDs) face notable difficulties in our society that uses colours as a tool of communication in various situations related to design, architecture, traffic, education, etc. Daltonization recolouring tools are a popular strategy in image processing to improve colour perception of people with CVDs by increasing chroma and lightness contrast between confusion colours that are difficult to discriminate for people with CVDs. However, recolouring tools often fall short in practical applicability due to not taking into account basic requirements of various colour tasks, and an insufficient assessment by real people with CVDs.

In this paper, we provide guidelines for the design and evaluation of Daltonization recolouring tools to increase practicability and enable their comparison with each other. Namely, a good recolouring tool for people with CVDs (i) should preserve naturalness and originality where possible; (ii) should preserve good colour identification and/or connoted meanings of colours. (iii) should sustain colour communicability consistently throughout the workflow; (iv) should enable customization for different types and severities of CVD of individual users (i.e., it should be open for the integration of different models of the human visual system (HVS)); (v) should define the visual goal of the recolouring tool; (vi) should name the target image type(s) of the tool, e.g. photographs, information graphics, maps, charts; (vii) should account for general restrictions of the medium both in acquisition and reproduction, and should acknowledge challenges related to colour management; (viii) must be tested using real observers with CVDs; and (ix) must be tested on different types of images.

Introduction

Colour is a widespread tool of communication in daily life used for conveying information in design, architecture, traffic, education, etc. However, about 8% of the male population has some Colour Vision Deficiency (CVD) that can significantly limit or obstruct the ability to differentiate certain confusion colours [1]. On the one hand, simulation methods can help designers, architects, engineers, educators, etc. to choose colours that are easy to distinguish by large groups of people with and without CVD. On the other hand, individuals with CVD can use automatic Daltonization methods that modify confusion colours in digital images to reintroduce lost information conveyed by colour. There are various Daltonization strategies including recolouring, texturing, labeling, colour-to-sound and colour-to-touch tools.

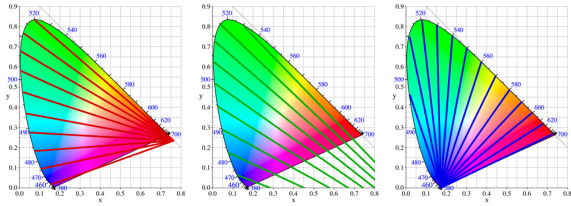
However, there has been no universally accepted agreement on what is the best strategy for a Daltonization method. Recolouring Daltonization methods, for example, improve discriminability of confusion colours by increasing colour hue or lightness contrast and are a popular solution in colour image research. Recolouring methods, though, have some significant downsides including the fact that they cannot create an adequate compensation for the lost colour information of people with CVDs and the fact that they often result in unnatural colours. Moreover, many studies fail in naming an explicit goal of the recolouring tool, and recolouring methods are rarely evaluated using real people with CVDs.

In this paper, we point out major structural and intellectual flaws that many recent Daltonization recolouring methods have in common. At the same time, we provide guidelines containing requirements and characteristics that should be fulfilled by a good recolouring tool. We offer ideas that should be considered when designing and evaluating a new Daltonization approach. We hope to provide some important aspects of Daltonization that will start a discussion on how to improve future recolouring tools.

Implications of Colour Vision Deficiencies

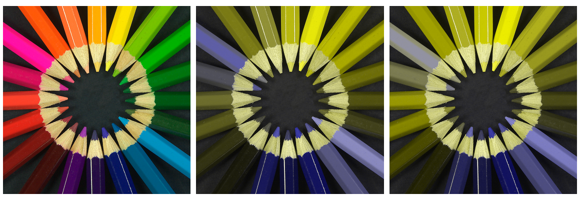
Colour Vision Deficiencies (CVDs) are caused by missing or anomalous cone types in the retina of the eye that result in reduced colour differentiation abilities and affect about 8% of the male population [1]. People who are missing one type of cones are called dichromats, whereas people who have a cone type with shifted sensitivity are referred to as anomalous trichromats [1]. Depending on the cone types affected, the CVDs are called protan (for CVDs related to L-cones), deutan (M-cones) or tritan (S-cones). For people with CVDs, certain confusion colours that are easily distinguishable for people without CVDs look close-to-identical. Confusion colours can be represented in colour space by so-called confusion lines that converge into different confusion points depending on the type of CVD (cf. Figure 1). Colours located on the same confusion line are perceived as being close-to-identical depending on the type and strength of CVD. Confusion colours illustrate why the colloquial term “colourblindness” for CVD is misleading: People with CVDs do not perceive the world in black-and-white but only have a reduced perceptual colour space. The perceptual colour space of people without CVD is often described along the dimensions black–white, red–green and blue–yellow, whereas the perceptual colour space of people with protan and deutan CVDs (the most common types) is typically described along the dimensions black–white and blue–yellow (for dichromats) or black–white, blue–yellow and a compressed red–green as compared to trichromats (for anomalous trichromats).

Trichromatic colour vision in humans evolved because it represents a significant behavioral advantage [3]. Colour, for exam-



(a) Protan (b) Deutan (c) Tritan

Figure 1: Confusion lines for different types of CVDs.



(a) Original (b) Protan (c) Deutan

Figure 2: Examples for different CVD simulations using the method proposed by Brettel *et al.* [2]

ple, helps in guiding attention to different elements in a scene, supports object recognition and, probably, supports the detection of emotional states [4]. We naturally use colours, for example, to easily find red berries against green foliage in the forest, separate ripe from unripe fruits like bananas in the store, categorize the preparation of a steak while cooking into 'rare', 'medium' or 'well-done', identify rashes and burns on the skin, etc. [5]. Colour vision incorporates, at least today, more than a behavioral advantage. In fact, the list of colour application areas is as long as the furniture of our natural and cultural environment and encompasses both practical, emotional and cognitive levels of human existence. An overview of situations where colour is used as a tool of communication are numerous and can, for example, be found in [6]. In settings of perception and communication, tasks involving colours can be categorized into (i) comparative colour tasks, where users have to state whether two colours are different or not, (ii) connotative colour tasks, where colours code certain information, e.g., green signaling 'safe to proceed' in traffic, (iii) denotative colour tasks, where colours organize complex visual scenes or highlight certain elements in a scene, and (iv) aesthetic colour tasks, where colours evoke a certain emotional response [6]. Colour application can also be categorized in other ways, but the crucial fact remains that the categories interact. Colour is widely used in design, architecture, traffic, education, religion, etc. as a tool of identification and communication. We socially use colours, for example, in architecture to highlight structure elements like exit signs, in design to organize visually complex layouts like maps, in traffic to signal when it is safe to go or when cars have to stop, and in education as a didactic helper to group and highlight certain ideas [7]. Colours can also have emotional aspects, for example, when we say that green is the colour of hope, or when we say that we are feeling blue when we are sad.

Many of the colour tasks listed above can be problematic for people with CVDs [6]. Steward and Cole [8], for example, showed that many people with CVDs report difficulties with some common everyday tasks, in traffic, and at work. Flatla and Gutwin revealed that some people report difficulties in judging the ripeness of fruits, the categorization of the preparation of a steak, the identification of rashes, etc. [5]. Work-related and shopping challenges have also been recently highlighted [9].

Although many challenges related to CVDs pose only a small risk, there are a number of more severe challenges too, such as limited choice of career (e.g., armed forces, border control officers, web designers, and dentists all require good colour vision), difficulties related to driving [8, 10], limited access to colour-coded information [11], and even threats to health and safety (e.g., misidentifying colour-coded medication).

Daltonization Recolouring Tool Limitations

The current trend of tolerance, inclusion, and non-discrimination – manifested in legal legislatures like the Norwegian Anti-Discrimination Bill [12], the Universal Design movement [13, 14], etc. – makes elimination of disadvantages caused by CVDs an issue of importance. Image processing science offers at least two strategies to help people with CVDs, including CVD simulation methods and Daltonization tools.

CVD simulation methods can emulate the perception of people with CVDs for people without CVDs (cf. Figure 2). Thus, designers, architects, engineers, etc. can use simulation methods to identify colours of elements in the design, layout, product or structure that might be difficult to discriminate by people with CVDs. This would allow these problem colours to be replaced with colours that are more universally discriminable by people with and without CVDs. In other words, simulation methods can help to choose colours that are more universally accessible for people with different perceptual capabilities.

In some cases, however, colours cannot be chosen freely (e.g., in photographs), or the choice of colours has already been made beforehand like in existing public transportation maps. To address these situations, Daltonization methods have been introduced to adapt colours in digital images for "improving the colour perception by [an observer with CVD]" [15]. More precisely, Daltonization methods change colours to make them more discriminable and more accessible for people with CVDs. Accessibility is a central concept in the field of universal design, which aims to make products and environments more usable by people with different capabilities - including people with and without CVDs [14]. Regarding Daltonization, accessibility is defined very broadly and depends, among other things, on the colour tasks mentioned above and described in [6]. In other words, improving accessibility for people with CVDs might include improving the ability to distinguish details, to more easily perceive colour contrast, to identify colour edges, or generally to facilitate the extraction of information from an image.

There are various strategies to implement Daltonization methods for different types of images. Milić et al. [16] proposed a classification of current Daltonization methods according to the characteristics of: (i) Content Dependency: A content-independent algorithm would always map one colour to one specific colour independent of the individual image; content-dependent methods map one colour to different colours depending on the image content. (ii) Processing Area: An algorithm following a total solution would change the entire image, whereas a partial solution would only adapt certain problematic areas of the image. (iii) Target Group: The image is optimized for both people with and without CVD in a universal design approach, whereas individual observers or groups of observers are targeted in a customized solution. (iv) Processing Control: User-assisted Daltonization depends heavily on user input parameters, whereas automated Daltonization does not require any parameter input by the user. (v) Enhancement Type: Reflects the approach taken to reintroduce lost information into the image and can change drastically between different approaches. Some algorithms recolour confusion colours in hue and/or lightness [15, 17–21], introduce texturing to coloured areas [22], or introduce colour labelling [23]. Moreover, there has been a discussion of possibly using sensory substitution devices (SSDs) as an enhancement type by reintroducing lost information using colour-to-touch [24] or colour-to–hearing mappings [25]. Studies suggest that sensory substitution may create an additional sense of the remapped information and artificially induce acquired synaesthesia [26]. Of all enhancement types, recolouring tools have been most extensively studied in CVD image processing research to-date.

The popularity of recolouring methods can be explained by the fact that they represent an efficient solution to the underlying problem of people with CVDs facing comparative colour tasks[1]: Recolouring tools often effectively increase the discriminability between confusion colours, they are relatively easy to implement across various media outlets, they require little to no adjustment time by the observer, they are scalable for different situations, at the same time as they conform to many of the principles of universal design including equitable use, flexibility, perceptibility, low physical effort, and size and space. [25].

However, there are some significant downsides of Daltonization recolouring methods related to the reduced perceptual colour space of people with CVDs, naturalness, and a lack of empirical assessment. First, recolouring methods cannot compensate for the lost perceptual dimensionality of people with CVD. In the ideal case, a Daltonization method would enable an observer with CVD to perceive the Daltonized image identically to how a person without CVD would perceive the original image. However, recolouring methods cannot achieve this ideal case of Daltonization because the recoloured images are restricted to the reduced perceptual colour space of the respective CVD - there are just some colours that cannot be perceived by people with CVD.

Second, recolouring often introduces problems related to naturalness. Recolouring often: (i) introduces new colour discriminability problems by recolouring non-confusion colours (when a variety of colours are present) or producing unpredictable recolouring results; (ii) destroys naturalness by interfering with the connoted meanings of colours (e.g., recolouring unripe bananas from green to blue); and (iii) prevents colour identification by destroying the original colour cues while providing no additional cues to help with the identification of colours (e.g., a rose is recoloured from red to purple). These downsides will make certain colour tasks considerably more difficult, especially connotative and aesthetic colour tasks. A complex solution to these problems could be strategies that help people with CVD perceive colours they cannot see with their eyes via mapping colour information to other visual stimuli (e.g., patterns or textures), auditory SSDs, vibro-tactile SSDs, or temperature SSDs.

[1]In this context, efficiency is defined by the resources needed to adapt colours in comparison to the accuracy and completeness of various colour tasks after Daltonization by the observers [27].

Third and last, the assessment of the improvement for a given recolouring method is often neglected in respective studies. An overview of weaknesses of current recolouring assessment can be found in Sections 2.7.3 & 2.8.3 of [28]: Many studies evaluate their respective method by individuals without CVDs or by only a small number of individuals with CVDs, they do not specify the exact goal of recolouring, they do not name the colour task they intend to improve, and they test their method only on a limited range of image types.

Guidelines for Recolouring Tools

The strengths and weaknesses of Daltonization recolouring methods described above, combined with their popularity in the CVD image processing community, should emphasize the necessity of a more general discussion for this particular type of Daltonization. To initiate this discussion, we introduce design guidelines and strategies for Daltonization recolouring tools to help researchers in finding adequate strategies when developing a Daltonization method. We are recommending requirements for colour changes, expectations from the resulting Daltonized images, and the necessity of evaluation by using observers with actual CVDs.

In the following guidelines, we define general Daltonization methods as any image processing techniques that modify colour images in any way to improve colour perception for people with CVDs [15]. Moreover, we define *Recolouring Tools* as Daltonization methods that adapt or modify the colours in colour images to increase chromatic and/or lightness contrast between confusion colours in a given colour space. The guidelines are grouped into design- and assessment-related recommendations. The design guidelines, on the one hand, recommend strategies to consider *before* implementing the recolouring method. They address issues and difficulties related to which confusion and non-confusion colours of the image should be recoloured and how colours should be changed. The assessment guidelines, on the other hand, set standards and requirements for the evaluation of recolouring tools *after* the recolouring tool has been implemented. They are necessary for "quality assessment" of a recolouring method, and they enable comparison with other methods.

A good Daltonization recolouring method:

1. Should preserve naturalness and originality where possible. Recolouring tools should preserve existing colours and contrast between confusion and non-confusion colours as much as possible. Some Daltonization methods increase contrast between confusion colours by shifting their hue or lightness [15, 17, 21], others return a Daltonized version of the original image in the reduced colour space of a virtual dichromatic observer [19, 29]. However, many recolouring tools that use static hue-shift solutions do not optimize for existing colours in the input image. In these circumstances, recolouring might introduce new problems into the image by shifting confusion colours to resemble non-confusion colours present in the image. In other words, the contrast between some confusion and non-confusion colours was perfectly distinguishable before Daltonization but has become indistinguishable after Daltonization. Thus, recolouring tools might facilitate comparative colour tasks to identify differences between the confusion colours at the expense of

decreasing the image gamut drastically. Likewise, recolouring tools that reduce the Daltonized image to a dichromatic colour space might, in fact, increase discriminability between confusion colours at the price of eradicating perfectly visible contrasts between non-confusion colours. To sum up, recolouring tools should preserve naturalness whenever possible, and also take into account colour differences between confusion colours and non-confusion colours.

2. Should preserve optimal colour identification and/or connoted meanings of colours. First, many recolouring tools seriously inhibit/prevent/reduce colour identification. Many hue-shift recolouring tools, for example, entirely change the hue of a confusion colour to guarantee maximum contrast to other confusion colours. A red flower might be recoloured blue, a red berry might be recoloured orange, or a red tomato might be recoloured cyan. These colour changes will not only change the overall aesthetic appreciation of an image but can also make object recognition more difficult [30]. Likewise, unfamiliar colours are most notable for memory colours that are important in the processing of the HVS [31]. Second, colours often have some emotional associations, physiological effects and/or symbolic connotations for the observer. For example, red and orange colours are often perceived as aggressive whereas green and blue colours are perceived more often as being soothing [32]. Green is known as being the colour of hope, whereas black symbolizes loss and sorrow in many cultures. Third, many artists compose colours deliberately to evoke certain emotional reactions in the observer. In these cases, recolouring confusion colours of an image might undercut the original artistic intention for a given artwork. The examples above show how recolouring tools might seriously impede the performance of observers with CVD in connotative and aesthetic colour tasks. To conclude, a good recolouring tool should preserve memory colours and subjective colour characteristics. It should also uphold the general aesthetic appreciation of the original image.

3. Should sustain communicability consistently throughout the workflow. We use colour to communicate and identify particular objects or elements. For example, public transportation maps assign specific colours to different subway lines, geographic maps associate geographic entities with various colours like blue for rivers and green for forests. Recolouring might, therefore, impede communication if colours changes are significant. A user with CVD might not be able to find the "green" subway line on public transportation map or the green forest on a geographic map because the colours have been changed to blue or orange. Consequently, communication with other people looking at the original image will be difficult. Moreover, colour has been characterized regarding hue, saturation/chroma, and lightness from the beginning of colour science research [33]. We can say that a shirt has a bright red colour, the grass is vibrant green, etc. By recolouring the colour of objects, these characteristics might be changed significantly. A bright object might become darker, whereas an object with high saturated colours might become almost neutral. Thus, recolouring should maintain the characteristics of a colour denoted by the human language of colour we use during communication as much as possible.

4. Should enable customization for different types and severities of CVD for individual observers (i.e., it should be open for the integration of various models of the human visual system (HVS)). Digital CVD simulation methods are an essential step in most recolouring tools, many of which use dichromatic simulation methods [15, 17, 21]. However, no single simulation method can universally represent the perception of every observer with CVD. Instead, there is a broad spectrum of CVDs in humans both in type and severity. In fact, colour perception differs even between people without CVDs [34]. Likewise, every person with CVD has an individual threshold at which confusion colours are perceived as being equal. It should thus be evident that there is no universal one-fits-all recolouring solution based on a static dichromatic CVD simulation. Instead, it is important to obtain simulations that are as accurate as possible for a particular observer with CVD. For example, some simulation methods can be personalized to represent specific CVDs more precisely [5,29,35]. They typically require precise input about type and severity of CVD to accommodate (e.g., [29]). However, many observers with CVDs do not know or do not remember these parameters, So recolouring tools should also provide a stage of calibration in which the individual CVD of the observer is assessed. One possible solution to evaluate individual CVDs and create customized simulations, for example, has been described in [5,11]. Last, we recommend a transportable construction of recolouring methods in which the simulation step can be exchanged for other modules. This module-based solution would also provide an opportunity to include different models of the human visual system describing more than the traditional protan, deutan and tritan CVDs like monochromacy, cataract, comorbid CVDs or reduced colour vision caused by aging.

5. Should state the visual goal of the recolouring tool. Many recolouring tools fail to deliver on the promise to maintain image quality or enhance images significantly. Studies often fall short in defining what the actual goal of the recolouring method is. The definition of Daltonization above, for example, only states "the improvement of colour perception" [15] without specifying what this enhancement contains in detail. Instead, the actual enhancement of recolouring depends strongly on the underlying colour task. One goal of recolouring methods could be, for example, to increase the ability of observers with CVDs to differentiate areas and details of confusion colours. It could also be to support the attentional mechanism in extracting relevant information from an image. Likewise, the goal could be to help the observers with CVDs in identifying objects more quickly like red berries in front of shadowed green foliage. Alternatively, it could be to enable the observer with CVD to identify colours more easily, etc. Depending on the specific task, recolouring tools will likely incorporate different strategies. Therefore, we argue that recolouring methods should define the specific colour task they intend to improve, for example, comparative, connotative, denotative or aesthetic colour tasks.

6. Should state the target image type(s), for example, photographs, information graphics, or maps. The requirements for different image types might change due to characteristics and challenges imposed by the image type. Photographs, for example, have a higher demand of preserving naturalness than charts or information graphics where colours can be used more freely and deliberately. Information graphics like maps, on the other hand, might have demands on preserving certain conventional colour connotations such as water on maps being depicted as blue, or that certain brand logos are depicted in trademarked colours. There are also other characteristics related to colour distribution that are more common for one type or the other. Photographs, on the one hand, often have smooth gradients due to shading and contain generally more desaturated colours. However, information graphics often have sharp, cartoon-like edges, and typically contain more vibrant colours.

7. Should account for general restrictions of the medium both in its acquisition and reproduction and should acknowledge challenges related to colour management. Digital colour images face considerable limitations, as compared to the capabilities of our human visual system. Mechanisms like colour constancy and white balancing are often hard to emulate especially in settings with mixed illumination (see Chapter 1 in [3]). For example, a photograph that has been obtained with an uncalibrated white point will consequently result in less than optimal Daltonization results. Moreover, there are certain gamut boundary restrictions in virtually all media devices. Media like print, screens, and projectors have a restricted gamut that covers less than what humans can perceive (often resulting in challenges for CVD simulation techniques that can push colours out-of-gamut). Daltonization methods should provide strategies to account for these kinds of problems. A recolouring strategy might, for example, include a white balancing step or seek to preserve memory colours.

8. Must be tested on real observers with CVDs. Many recolouring methods have been evaluated by very few people with CVDs (see Sections 2.7.3 & 2.8.3 in [28]). Evaluation is often replaced with CVD simulations of the Daltonized images evaluated by people without CVD. However, as discussed before, many CVDs differ widely in type and severity. Thus, a CVD simulation method is often suboptimal for evaluation. Moreover, a simulation can only approximate CVDs to some extent. Researchers without CVDs also have to be aware that they have to interpret the simulation with respect to the reduced dimensionality judged by someone with a wider perceptual colour space. Simulated images that emulate dichromatic or anomalous trichromatic colour vision represent an image with reduced gamut by definition. Thus, colours look unnatural and/or pale for somebody with trichromatic vision. However, a dichromatic or anomalous trichromatic observer is not aware of the wider trichromatic colour space. He/she grew up with his/her respective CVD, and his/her HVS learned to adapt to the restrictions in perceptual colour space since birth. Thus, many aspects of simulated images such as naturalness, colour identification, or pleasantness of CVD-simulated images are difficult to understand for people without CVD. We suggest, therefore, the evaluation of recolouring tools by people with CVDs using various methods provided by behavioral and/or psychometrics as we presented in [11, 36–38].

9. Must be tested on different types of images. Many recolouring studies do not test their corresponding methods on a broad spectrum of different image types as we discussed in Sections 2.7.3 & 2.8.3 of [28]. A recolouring tool might target different types of images like information graphics, maps or photographs, as we discussed before. It should be required for every recolouring method to be tested on various image types to identify images that work well (or not) with a given recolouring tool. In [36], for example, we introduced an assessment method for Daltonization methods that uses test images spanning a wide variety of different colour image types and attributes. The recolouring tool should be tested for different image settings. Evaluating the recolouring on Ishihara plates only is not sufficient since Ishihara plates do not represent typical photographs.

Conclusion

In conclusion, a recolouring tool should change the image as little as necessary and should be assessed as thoroughly as possible. Recolouring should (i) preserve the naturalness of the image in general, (ii) keep individual colour characteristics as much as possible, and (iii) sustain colour communicability consistently across the workflow. (iv) It should state the colour tasks it intends to improve, and (v) the target images it uses. (vi) It should be customizable for individual CVD types and severities, and (vii) account for colour management across different media devices. (viii) Finally, it must be tested on different types of images (ix) by real observers with CVDs. The previously discussed guidelines related to design and the evaluation of recolouring methods will help scientists to account better for the needs of people with CVD facing various types of colour tasks and facilitate scientific evaluation and comparison between different Daltonization strategies.

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Author Biography

Joschua Thomas Simon-Liedtke received a joined M.Sc. in computer science from Høgskolen i Gjøvik, Universite de Saint-Etienne, and Universidad de Granada in 2013. He is currently a Ph.D. student at NTNU Norwegian University of Science and Technology, focusing on image enhancement for people with CVD.

Dr. David R. Flatla (BA, BSc, MSc, Ph.D.) is a Lecturer and Dundee Fellow within Computing at the University of Dundee, Scotland. David leads the DAPRlab (Digitally-Augmented Perception Research Lab) research group that combines sensors and wearables to enhance the day-to-day perceptual abilities of everyone – both people with impaired sensory capabilities as well as those with typical abilities. David's personal research area is in modeling, simulating, and creating assistive technology for Impaired Colour Vision.

Eskild Narum Bakken (BA, MA) is lecturer and researcher of architecture, universal design, and aesthetics at NTNU Norwegian University of Science and Technology, connected to Norwegian research laboratory of universal design. He holds university degrees in architecture, philosophy, art history, psychology, medicine and sports science. His teaching and research in colour and visuality are taking a holistic view on perception, such as addressing the interaction of accessibility and aesthetics related to colour.