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Lighting Perceptual Intelligence

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Abstract
Perceptual Intelligence concerns the extraordinary creative genius of the mind's eye, the mind's ear, etcetera. Using π humans actively construct their perceptions of the world. We need a thorough interdisciplinary understanding of these mechanisms in order to be able to design perceptually intelligent products (including tools, systems and services). Using a new science of lighting as a vehicle, we will concretize this scientifically informed design approach, its possibilities and challenges in a dynamic complex world.

1 Introduction: perceptual intelligence

With Perceptual Intelligence we mean the extraordinary creative genius of the mind's eye, ear, etcetera, which, far from being passive recorders of a preexisting world, actively construct every aspect of our perceptual experience, analogous to Donald Hofmann's definition of visual intelligence [Hofmann, 1998] Our perceptions often comply with template-like presentations [Koenderink, 2014]. For instance: if observers have to adjust a box space's depth they tend to do it in a standard manner, irrespective of the viewing distance and size [Pont et al., 2012]; real-world objects have a fixed visual size or canonical visual size [Konkle and Oliva, 2011]; illumination estimates comply with uniform, divergent and convergent light fields, observers tend to neglect deviations from such patterns and are blind to deformation and rotational patterns [van Doorn et al., 2012; Kartashova et al., 2016]. In art and design such template-like presentations are often used as perceptual triggers [Crilly, 2004; Cavanagh, 2005; Perdreau and Cavanagh, 2013; Mamassian, 2008]. The manner in which this usage is named and explained varies from tricks and conventions to simplified physical models, suggesting less or more explicit understanding of the physical and perceptual processes behind the final resulting experience. We strive for a thorough understanding of these mechanisms in order to be able to make perceptually intelligent products, systems and services, which we call perceptually intelligent if and only if users experience them as such. In the sequel we will describe examples and discuss related challenges.

Leonardo da Vinci already noted: "*To develop a complete mind: Study the art of science; study the science of art. Learn how to see. Realize that everything connects to everything else.*" This connects to another aspect of perceptual intelligence, namely one in which it is studied how we can enlarge our ability to perceive what's there. This connects to literature about art and developing skills to *represent* what's there. However, the majority of available materials about developing skills to *perceive* what's there in the generic sense (in all contexts) concerns non-scientific reports which were not formally evaluated. Recently however scientific interest in this topic was raised and first ideas were implemented to explore this field, namely art observation as a means to enlarge the observation skills of medical students [Elbert and ten Cate, 2013]. These ideas raise many questions, such as what these abilities encompass and whether they indeed generalize to other contexts. Below we will further discuss this topic.

Perceiving is an important skill for designers and therefore should be part of our education (we teach at Industrial Design Engineering, Delft University of Technology). We study and teach about light, that is, how we see light, how we can describe and modulate its physical form and our experiences, and how we can design light, that is light, not lamps, and our interactions with it. Now normally we see the light via the appearance of our environment and the objects and people in it, not by looking at the sources directly. In figure 1 for instance we see light in front of a wall … but you cannot see it. But, if we put something in the light you will be able to judge its qualities, see figure A1 in the appendix. Did you expect more diffuse light than what the *light probe* in figure A1 shows? That might have to do with yet another template, for moderate levels of light diffuseness, as Morgenstern et al. have shown [Morgenstern et al., 2014]. Because we see a strong texture gradient, highlights and a dark shadow on the light probe, we know that the light is strongly focused. In order to design light one should learn to see these qualities. Below we will give many examples from our studies and education in light and its interactions with materials, shapes and spaces, to illustrate our thoughts with concrete examples. Moreover, we will report on our experiences with learning how to see, of ourselves and with students.

Finally, recent techn(olog)ical innovations such as LED lighting, miniaturization of LED's and sensors, integration of internet in things, etcetera, go in a direction that brings lighting and imaging science closer and closer to each other [Heynderickx and de Ridder, 2013]. In these developments it would be good to connect both worlds in order to not re-invent the wheel.

Figure 1 light in front of a wall

2 Developing the field of scientifically informed, perceptually intelligent light(ing) design

2.1 The science of perceptually intelligent light

Light influences how things look. In figure 2 for instance we see, at top left, a card illuminated by frontal lighting, and at top right the same card but now illuminated by grazing lighting. Frontal lighting makes 3D relief invisible. It is the type of lighting that is usually on an endoscope, a medical instrument to do surgery (which thus forms a problem for the doctor who needs to judge the relief and shape of tissue). Under grazing lighting we can see the 3D relief and shapes. In the bottom row we see textile samples illuminated by quite diffuse illumination at left and by quite directed illumination at right. The perceived glossiness, but also metallic-ness, softness, cleanness, etcetera vary with the illumination [Barati et al., 2017]. Similarly light can make colors, textures, gloss, glittery-ness, velvetiness, translucency, transparency, luminescence, sparkle, etcetera, more or less visible.

How we visually experience such light-shape-material interactions is determined by optical effects and perceptual mechanisms. Even though optical effects can be small, they can have a big perceptual impact, such as the slight brightening of contours due to asperity scattering of downy hairs on skin [Koenderink & Pont, 2003], or vice versa, as a result of perceptual constancy mechanisms. Light-material interactions are not symmetric and depend on the type (canonical mode) of light and material [Zhang et al., in preparation]. We expect that light-shape-material interactions also depend systematically on shape type.

Light-shape-material interactions are due to image ambiguities: the resulting appearance is confounded and the inverse problem (inferring the high-dimensional physical properties light, shape and material from a 2-dimensional image) cannot be solved uniquely. Vision is not inverse optics. It is intelligent problem solving. In the case of light, material and shape, the confounded appearance is the starting point, and not the physical parameters on which it is based. The image of the confounded appearance is the primary input and we need to study which cues that image contains – including all its ambiguities – and relate that to our perceptions. This demands a fundamentally different approach to perception research than the classical psychophysical approach.

Figure 2. Top: a blind print under frontal illumination (left) and grazing illumination from above (right). Bottom: six textile samples under hemi-spherical diffuse illumination (left) and quite directed illumination (right).

So how can we get a grip onto this seemingly endlessly complicated problem? In our research, we approached this problem by categorizing light and materials into canonical modes [Zhang et al., 2015; Zhang et al., in preparation]. These categorizations were based on former research into the optics and perception of light and material reflectances. The modes can happen in isolation, but also in mixed combinations, as the sliders on the DJ mixing table - allowing weighted superposition models. For light we found four basic modes: ambient, focus, squash and texture. These modes can be quantified based on spherical harmonic analysis, which turn out to have a meaningful physical correlate and, moreover, can be estimated and adjusted by human observers. Additionally, at a phenomenological level, these modes are also found in art and design treatises as basic modes of lighting. For materials we started with a basic set of reflectance modes, namely diffuse, forward, and asperity scattering, which are perceived as matte, glossy and velvety materials. We expect that to cover the full range of materials we need about a dozen of modes. However, several studies using our first categorizations resulted in meaningful insights, and support the approach taken. We thus expect that the "canonical modes" approach forms a manner to get a handle onto the complexity of natural scenes.

To understand how we "experience" light we need more than understanding physics and perception. Experience also includes the meaning we associate with the appearance of a certain scene (and we will not go into non-visual aspects). The meaning which we associate with lighting was coined "lighting atmosphere" and it can be robustly measured [Vogels, 2008]. Vogels found that lighting atmosphere can be described by four factors: cosy, lively, tense and detached. In several studies it was found that these factors depend systematically on basic lighting parameters [Seuntiens and Vogels, 2008; Stokkermans, 2018].

Thus, basic ambiguities in the visual input result in perceptual interactions. These interactions can be studied and understood via a canonical modes approach. Understanding these interactions and the mechanisms behind our interpretations will allow us to design experiences in a scientifically informed manner.

2.2 The design of perceptually intelligent light

In Wikipedia we find that "Intelligent lighting refers to … lighting that has automated or mechanical abilities beyond those of traditional, stationary illumination. Although the most advanced intelligent lights can produce extraordinarily complex effects, the intelligence lies with the programmer … rather than the instruments or the lighting." With intelligent lighting we mean something different. We mean that it is designed for its users, that it gives the right experience at the right time and the right place. That experience will in most cases not involve conscious experiences of the light(ing) itself, but instead that of atmosphere, space, furniture and furnishing, etcetera. Thus, a well-designed light plan should be focused on how to bring out atmosphere, space, and the people, objects and materials in it. This involves a complex chain of thinking, in which the designer has to first define the requirements and final experience, or perceived appearance and atmosphere, then back-reason to the perceptual properties of the plan, then to the physical properties of the plan, and finally to the technical definition of the plan. The final implementation involves knowledge about available technology, and a lot of engineering to optimize the result. Most of this chain was conceptually framed in the atmosphere circle model [Vogels, 2009; Heynderickx and de Ridder, 2013;

Stokkermans, 2018]. We extended this model with appearance, and the engineering link between perceived appearance & atmosphere and the technology of the system, see Figure 3.

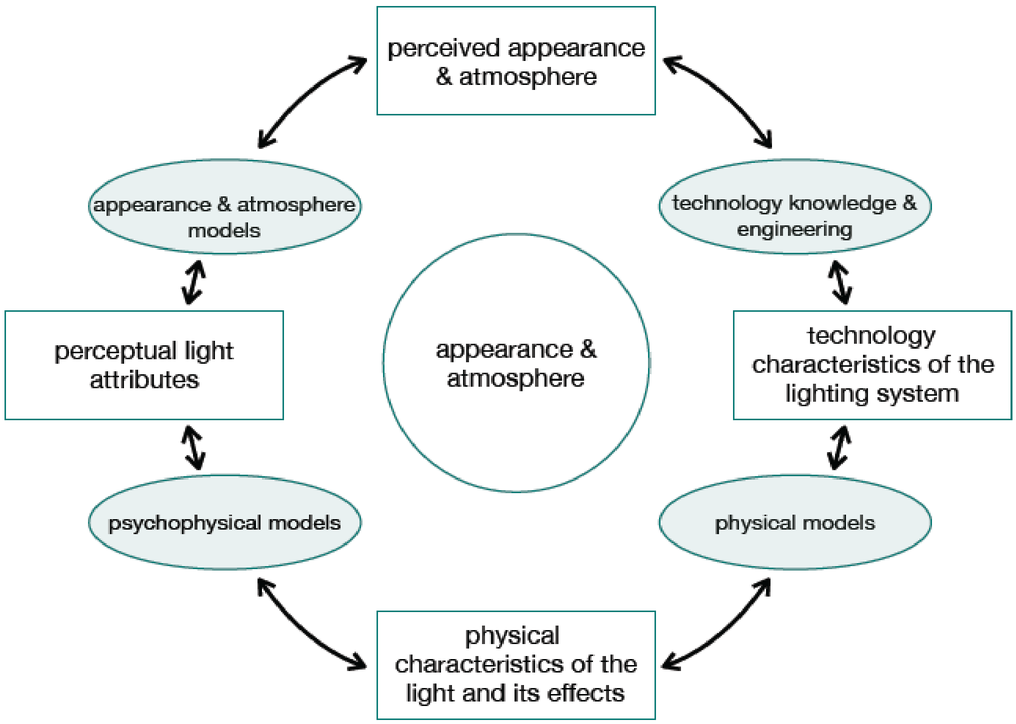

Figure 3 The atmosphere circle model. Figure based on Stokkermans et al. [Stokkermans, 2018], with our own extensions for appearance and the engineering link between perception and technology.

In practice, designing a light plan is not such a linear process. Often it involves a lot of iterations, piloting, simulations, adjustments and testing (and in that sense shows many similarities with designing a good psychophysical experiment). Moreover, forming a design vision on the basis of an analysis, designing a desired appearance on the basis of the requirements and design vision, translating that to a description of the light and filling in the technical details are steps that need specific skills and expertise.

2.3 The education of perceptually intelligent lighting design

Light is intangible. It only becomes visible through its interactions with an environment. Those interactions are hard to predict, optically as well as perceptually.

Optically the final appearance is the result of complex effects of shadowing, shading, scattering, vignetting, (inter)reflections, transmission, etcetera. Even the most sophisticated rendering programs cannot perfectly predict the end result physically realistic, because geometric models, material reflectance models and lighting models never exactly match the real situation, see Figure 4. And the perceptual effects are even harder to predict in natural, complex scenes. So then how can we teach students to design light in a scientifically informed manner – while preserving their creativity? How do we educate our students in terms of knowledge and sensitivity to the visual phenomena, in other words, learn to see the light?

At Delft University of Technology we teach our industrial design engineering students to design an integrated light plan in one 6ECTS Master elective course. Before the course they do not receive any training in light(ing) – they do however master a broad range of design methods and skills. The course aims are to provide a broad overview over issues and stages in lighting design, insights into basic physics, perception and design principles for light(ing) and understanding of functional, experiental and aesthetical aspects of light. We do this via a capita selecta series, practical training, excursions, and a design assignment to learn to work out a lighting plan in a principled manner, following a systematical framework linking design, perception and physics. The course starts from the idea that what we see is instances of the light field (the luminance as a function of position and direction), which is the result of complicated interactions between primary illumination, scene architecture, objects and materials (note: if one uses a specific kind of lamp or lighting, the resulting light field will be different in a black and in a white room). We aim to design that resulting light, through lighting. That may seem complicated, but using the canonical mode mixing approach explained above, illustrated with demonstrations and simulations, the students are able to understand and work with the ungraspable material light quite quickly.

As mentioned above the course includes practical training. These include small scale trainings in the class room as well as large scale training testing out lighting concepts outside, in the evening, on buildings / squares / bridges / trees / etcetera. During such workshops it often happens that students exclaim “Aha!! Now I see it!” Many of such informal observations through the years showed that practical training is necessary to get a grip on this “matter”. After the course the students have a good overview of the possibilities for lighting designers and what it needs to become one, and they delivered a first light plan. The companies involved in these assignments usually consider those light plans as inspiring and most of them containing fresh ideas that can be implemented in the corresponding or other projects.

Figure 4 Left: a computer rendering of a part of a lighting plan. Middle and right: two photographs made during an evening workshop, in which the intended visual effects were tested. Middle: a photograph in which the colors of the canopy show two different colors – tree colors appear very sensitive to the exact lighting spectrum and it is advised to always test such effects on the spot. At right a photograph of a test of the lighting of the curb, for which the direction and beam shape are important determinants of the effects. In the rendering these could be fine-tuned quite easily – but due to the simplified material models the effects of the grazing lighting on the cobble stones could not. (and actually resulted in a very nice texture)

3 Possibilities and challenges

3.1 … for the intelligent light(ing) realm

The approach using canonical modes works well in practice – that is, as a research tool to build interfaces, to analyse complex natural stimuli, and to design with. A first question that comes to mind however is how many modes we need to describe light, or materials, or shape. Do these modes need to agree with basic perceptual templates to create a perceptually intelligent framework? Is such a framework scale invariant? Future work in optics, computer science, perception and design research will hopefully shed light onto these questions.

A first major challenge that we will address lies in the "texture" part of the light. It is currently technologically easy to create spatiotemporal variations of lighting, because of novel technologies. LED's and sensors become smaller and smaller. They can be integrated in anything, combined with innovative and smart materials, internet and data-analysis, allowing the design of smart materials and smart interactive dynamic environments. However, interactive lighting designs currently still primarily encompass on/off and dimming protocols with simple presency detection, "me and my shadow" types of designs [Koerner], and preprogrammed atmospheres / scenes. True interactive lighting that is perceptually intelligent in the sense that users will experience it as such is still to be designed. Differences between lighting and imaging applications are disappearing [Heynderickx and de Ridder, 2013], see for instance the Philips Luminous panels, and media facades, and many other examples of dynamic and patterned lighting [Koerner]. Connecting these knowledge areas would benefit both realms.

Designers currently explore spatiotemporal light textures widely, but scientifically we do not yet have a systematic manner to describe, measure and visualize their perceptual properties. We believe that, for the light texture mode of our framework, the statistical properties are the main determinant of our experiences and that its variation through space can largely be neglected – in contradistinction to the light ambient, focus and squash. We will study how to describe these statistics, test how possible statistical modes of light textures are perceived, integrate it in our modes system, and evaluate the use of such an integrated approach.

3.2 …for the perceptual intelligence realm

Spatiotemporal dynamics will also form a major challenge for perception research in a general sense. Real world perception involves integration across time, space, and the senses, while moving and interacting with this world. Understanding such dynamic multisensory processes is key to many applications in real and virtual environments. Multidisciplinary collaborations between imaging science, psychology, neuroscience and design will benefit this direction greatly.

Next to these more or less logical extensions of past and ongoing research, we see another interesting possibility based on a collection of informal observations:

- In our lighting education we had students exclaiming "Aha!! Now I see it!" during active training – observing the effects of their own manipulations of lamps, filters, lenses, mirrors, etcetera.
- After psychophysical experiments in which we used paintings [Wijntjes and de Ridder 2014; Kartashova et al., 2015; Di Cicco et al., 2018], see Figure 5 for an example, we experienced seeing a visually much richer image if we saw the real painting after one or more hours of actively doing settings of perceptual probes or judgments.
- In a course on product experience we saw a large difference in the results of visual analyses

for students who received design drawing training and those who did not – the students who did were overall much better able to describe the attributes of materials, shapes and lighting. This observation shows obvious analogies with reported effects of training in art history [Perdreau and Cavanagh, 2013]. Taken together, these informal observations suggest that inter-active observation of imagery might help to *learn how to see* as DaVinci named it.

This idea also raises many questions, such as where in the human visual system this increased sensitivity originates, what kind of interactions would optimize learning results, to what extent learning results might generalize, and how we can extrapolate these studies to multisensory perception. Thus, we are facing challenges to first formally validate such learning effects and study the foregoing questions. We believe that this might lead to valuable applications for training and support of the development of perceptual intelligence.

Figure 5 An interface used in an experiment to test light perception [Kartashova et al., 2015] – observers had to adjust the illumination on the sphere such that it would fit into the scene, for multiple positions and multiple paintings.

Conclusions

We presented a view onto scientifically informed, perceptually intelligent design. We illustrated our thoughts with concrete examples of our research and education in light(ing) – oddly enough the least concrete "stuff" in our environment, but therefore perhaps also one of the best vehicles to "make one see the light". We described possibilities and challenges, needing a multidisciplinary approach, and broadening of the view to dynamic multisensory perception. We propose an approach to perception research that includes the complexities of the real world, making it manageable via canonical modes.

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Appendix

Figure A1. Light in front of a wall, with a "light probe" –an object to visualize the light qualities- in the light. Here we use a golf ball for which it was proven that the intensity, direction and diffuseness of the light can be judged well from the shad(ow)ing and 3D texture gradients [Xia et al., 2014].