Chapter 26

The Experience of Dynamic Lighting

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Additional information is available at the end of the chapter

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Abstract

The experience of the dynamic flux in daylighting is a complex relation between experiential and perceptual modalities, spatial presence of lighting qualities, and the architectural situation for the experience. In architectural practice, the understanding of daylight influx is key to the design of daylight openings and the experience of spatial form. However, current developments in light-emitting diodes (LED) light sources and adaptive software control systems allow for an enhanced correlation between daylight and artificial lighting, where the variations of the daylight are dynamically supplemented by variations in the artificial lighting. It is recommended that a particular type of Observational Instrument is developed, which situates detailed experiential investigations into the design potentials of integration of natural and artificial lighting and thereby enables differentiated dynamic lighting design in architecture.

Keywords: architecture, adaptive lighting, perception, perceptual training, perceptual reasoning

1. Observing the spatial distribution of light

The experience of spatial distribution of the daylight influx is complex. The experienced light formations are a result of a series of operations. The influx has its origin in an advanced composite of direct light, diffuse light, and reflected light from the environment, which is then formed by the daylight openings such as windows. Entering the architectural space, the light influx is then redistributed by shapes and surfaces and refracted and reflected in complex routes and operations. Further, the composition of the daylight influx is highly dynamic and transforms its composition and distribution throughout the day, often in speeds and changing patterns that make the dynamic variations the dominant form factor of the experience of daylight. The research leading to the design of the Observational Instrument (**Figure 1**) has been concerned with how to enable observations of the experiential qualities of the spatial distribution of dynamic daylight.

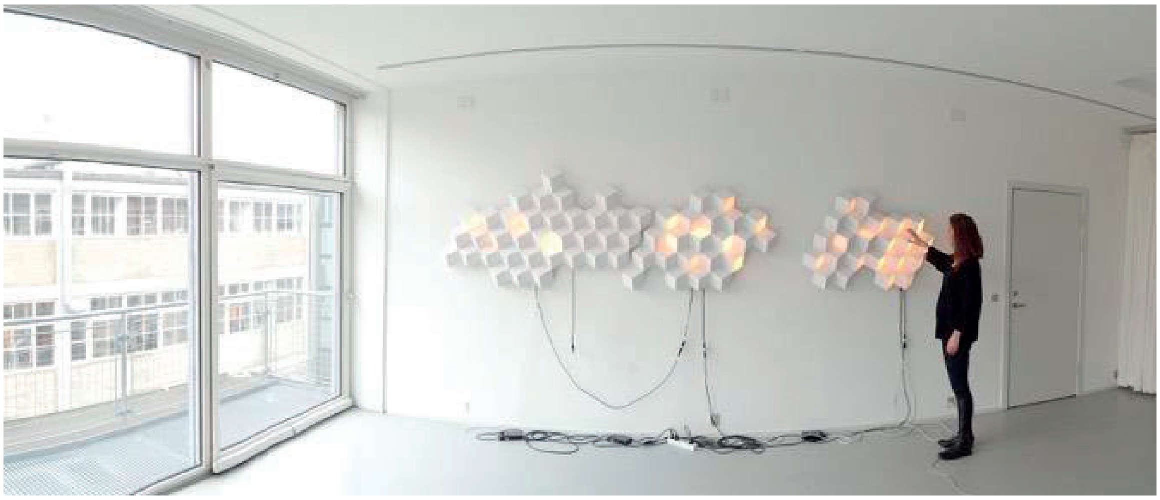

Figure 1. The Observational Instrument installed at the daylighting lab at KADK in Copenhagen. Window facing east; overcast day at noon.

The Observational Instrument is in the current version, an artefact composed of a tessellated pattern of square cubes, organised in an overall form that seeks to make the instrument neither a part of the wall nor a separate object in itself, but situated in-between these experiential categories. The Observational Instrument is slightly detached from the wall, and composed in a slightly fragmented way, in an attempt to enable focus on the light formations rather than the wall or the object. The size of the Observational Instrument, reaching from the light influx of the window to the darkest end of the space, allows for observations across and in depth of the space. The single cube elements hold the analytic form that enables a simplified observation of the light distribution in space. These cube objects divide the incoming light at that particular point in space into three main directions: one up, one towards the incoming light, and one away from the incoming light. An otherwise diffuse composite light formation at that particular point is by the cube separated into a clear division of direction, enabling an analysis of how the local light is composed of light from these three directions.

The tessellated design of the analytic cubes in the Observational Instrument allows for enhanced experiential observations. The pattern and size of the cube elements allows for perceptual comparison across the instruments, comparing lighting appearances on similarly shaped objects across space. The systematic view of lighting conditions serialised by the cube object also to some extend reveille the observations slightly from the very significant perceptual processes of 'perceptual constancies' [1], which seek to interpret the light formations along a surface, such as this wall in **Figure 1**, as one uniform spatial presence with almost even colour and light distribution. Having separated the spatial distribution of light into a series of identical triplet occurrences, the instrument opens for clearer observations on the dynamics of changes across the pattern.

The cube elements in the Observational Instruments are constructed with tuneable white light-emitting diodes (LED) behind each surface, as separate luminaires with each of their separate controlled dynamic of colour and intensity. The design enhances the subtle integration of the light reflected in the surface and the light emitted through the surface, and in this way, enables experimentation with the nuances of integration of daylight influx and artificial light emitted from the instrument.

2. The experience of light as perceptual engagement

The architectural lighting designer Lam [2] introduced similar concerns and approach to lighting design in his seminal work 'Perception and Lighting as Formgivers for Architecture' in 1977. The basic assumption is that, given the perceptual dynamics of the human, and a perspective on architecture as form emerging out of perceptual activities, there is an interest in how architectural form appears as visual impression of form. In Lam's view, the experiential processes of perception of lighting and architectural form is not a passive process, but an integrated part of our activities, sense of place, orientation, and history of inhabitation, which is negotiated relative to what we do, what we see, and how our perceptual processes operate. These experiential perspectives are similarly argued as essential to architectural form and design of lighting by Rasmussen in his book 'Experiencing Architecture' [3] and seen from a philosophical perspective in Nöe's 'Action in Perception' [4]. Rasmussen presents a set of form factors as a suggestion for an experimental approach to architecture, and Nöe investigates the consequences of how, for instance, light and environmental form appears if we understand perception as something we do rather than something that happens to us. In her PhD thesis [5], Karin Søndergaard further offers the design considerations that emerge when designing for participatory experiences, a perspective that further involves the social and relational aspects of perceptual engagement as framing agencies for the particular experience of place, environment, and event. For a more general introduction to the field of daylighting design and integration with artificial lighting, please consult Cuttle, Mathiasen, Madsen, and Tregenza [6–9].

The goal of the Observational Instrument is deliberately spatial, in the sense that the observers move and relocate across space while observing, and that the actual architectural forms and the relations to fellow inhabitants is a crucial part of the analytic activities. Analysis and considerations on lighting dynamics is an active performance of observational activities. The situation surrounding the Observational Instrument involves the experience and perception of the light and visual adaptation as part of the analytical context [10, 11]. The interrogation of the light in the space is based on the perception and experience of light as a relational experience rather than on measurements of light. Moreover, there is a focus on how the experience of lighting formations can be understood as spatial parameters. The Observational Instrument stages an architectural situation, a full-scale installation in any space of interest, where the influx of daylight can be observed, and the potential integration with artificial lighting dynamics can be investigated. The instrument enables a situation, where perceptual processes are actively incorporated in the event, through perceptual training and perceptual reasoning, while adjusting on incidents of lighting dynamics.

3. The composite of light from outside weather conditions

The fluctuation of daylight is an everyday experience of almost endless variation, observed as a direct consequence of the weather conditions and the composite of reflections from the environment. Components of sunlight and the luminous sky are modulated by dynamically changing cloud formations. Variations with larger duration are formed by the cycles of day and night, time of the year, and geographical position. These repeated operations form recognisable and predictable patterns that inform interpretations of orientation, shape shadows, and light distribution and change composition of colour temperature and luminous intensity. The variations during the day create a range of differently tinted colours, different angles of light, and different luminous intensities (**Figure 2**).

The morning light often starts in blue colours and shifts through a palette of variations into the whiter daylight. During evenings, the variation follows similar transformations, continuously and repeatedly unfolding the full range of dynamics, colours, and intensities possible.

Figure 2. The dynamic and complex daylighting flux. These images are from the same location photographed only 20 minutes apart.

Clear sunlight produces sharper light zones, distinct shadows, and bright glare. Overcast days produce blurred light zones, diffuse shadows, and more evenly distributed colours and luminous intensities. The composite of the daylight influx is projected through the openings of the building, literally as project images of the outside, appearing upside down and reversed due to the camera obscura lens effect of the daylight openings, such as windows. The daylight in the building is a direct effect of the outside illumination and includes every reflective and shadowing element present, such as reflection of light from grass, trees, traffic, houses, etc. All these elements contribute to the complex composite of daylight influx and offer nuances to the visual experience of the indoor space.

The images in **Figures 3–5** depict two instances with very different lighting condition, **Figure 3** with diffuse light reflected from the opposite wall, **Figure 4** with direct sunlight on the Observational Instrument, and **Figure 5** in early morning light, resulting in very different colour tone and luminous intensities on the floor, the ceiling, and the wall. In **Figure 3**, the floor reflects the bluish sky, the wall the reflected sunlight, and the ceiling the combination of the green grass and the light reflected by the yellow brick building outside the window. In **Figure 4**, all internal reflections are dominated by the direct sunlight influx. In this way, every element in the surrounding environment is a component in the composition of the daylight influx in constant recomposition driven by time of day, weather, and environmental reflections.

Figure 3. The Observational Instrument with diffuse light from sunlight reflection at 11:40, April 30, 2014.

Figure 4. The Observational Instrument with direct sunlight influx at 9:20, April 30, 2014.

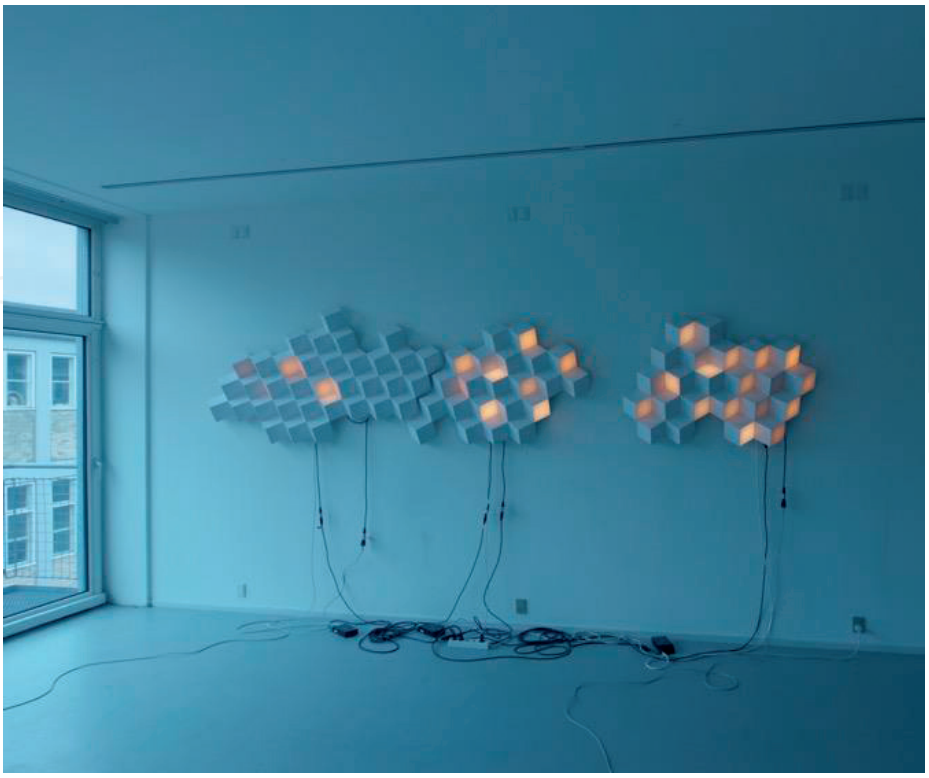

Figure 5. The Observational Instrument early morning at 7:30, April 30, 2014.

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4. The digital weather

Taking the offset in the dynamic rather than the static lighting qualities, the design of the Observational Instrument is based on the concept of an artificial weather system. The digital weather software is in constant flux with dynamic parameters of adjustment, to be able to integrate with the complex of the natural weather variations through compositions of changes, dynamics, scales, and specialisation. The animated artificial light is projected from inside each surface of the cubical elements in the instrument, which enables separate adjustments in every direction of a cube and across the tessellated cube elements. The digital weather can be set to produce a dynamic composition that is reminiscent of the pattern similar to the effect of cloud variation in the sky, simulating dynamics that sometimes is composed with larger contrast and faster flow, and sometimes with delicate variations and almost imperceptible dynamics. The intent is to be able to develop complex compositions of dynamic flux in the artificial light that allows for integration with daylight flux as an ambient experiential material. The suggestion is that with the composite and dynamic weaving of light variations reminiscent of daylight fluctuations, the Observational Instrument gives access to investigations into dynamic relations and dynamic developments of integrated daylight and artificial lighting that otherwise is difficult to approach as material for architectural lighting design.

The software is built around the Perlin Noise algorithm, which is actually not a ‘noise’ in the sense of introducing uncontrolled variations, but a procedural generator [12] that is designed specifically ‘to produce natural appearing textures on computer generated surfaces’ [13]. The software is designed to perform two separate operations: one for generating kelvin variations and the other for generating luminous intensities. These two are layered and the combined expression makes the output for the light qualities at any particular point in space. The Perlin Noise algorithm is spatialised and negotiated as a two-dimensional space with fluctuations appearing across the space as waves, rhythms, speeds, and progressions, organised into larger formations of collective patterns and individual agencies (**Figure 6**).

The access to the generative parameters in the Digital Weather software is organised in scales and termed as Range, Speed, and Spread. The Range parameter sets the scale within which the colour or luminous intensity can change, with a minimum and maximum level. This adjustment could, for instance, determine, in the case of direct sunlight, that the variation in luminous intensities are only within the highest levels, but the change in colour spans the whole range possible. The Speed parameter determines how fast the dynamics unfold: from the slowest and almost imperceptible changes, through rhythms of waves, into rapid flickering. The Spread parameter determines the spatial composition of the light variations, in a scale where the extremes allow for totally individual behaviour of each LED, through to collective behaviours across the Observational Instrument as patterns and flows (**Figure 7**).

The Observational Instrument produces continuous fluctuating light compositions, which can be adjusted in how the dynamics unfold. Adjusting the settings allows for experimentation with how range, speed, and spread of artificial lighting dynamics are experienced to relate fluctuations in daylight. The effort of the adjustments can be difficult to eliminate the difference and thereby simulate dynamics similar to the daylight dynamics, which produces a digital formula on that particular dynamics in the settings of the instrument. There can be

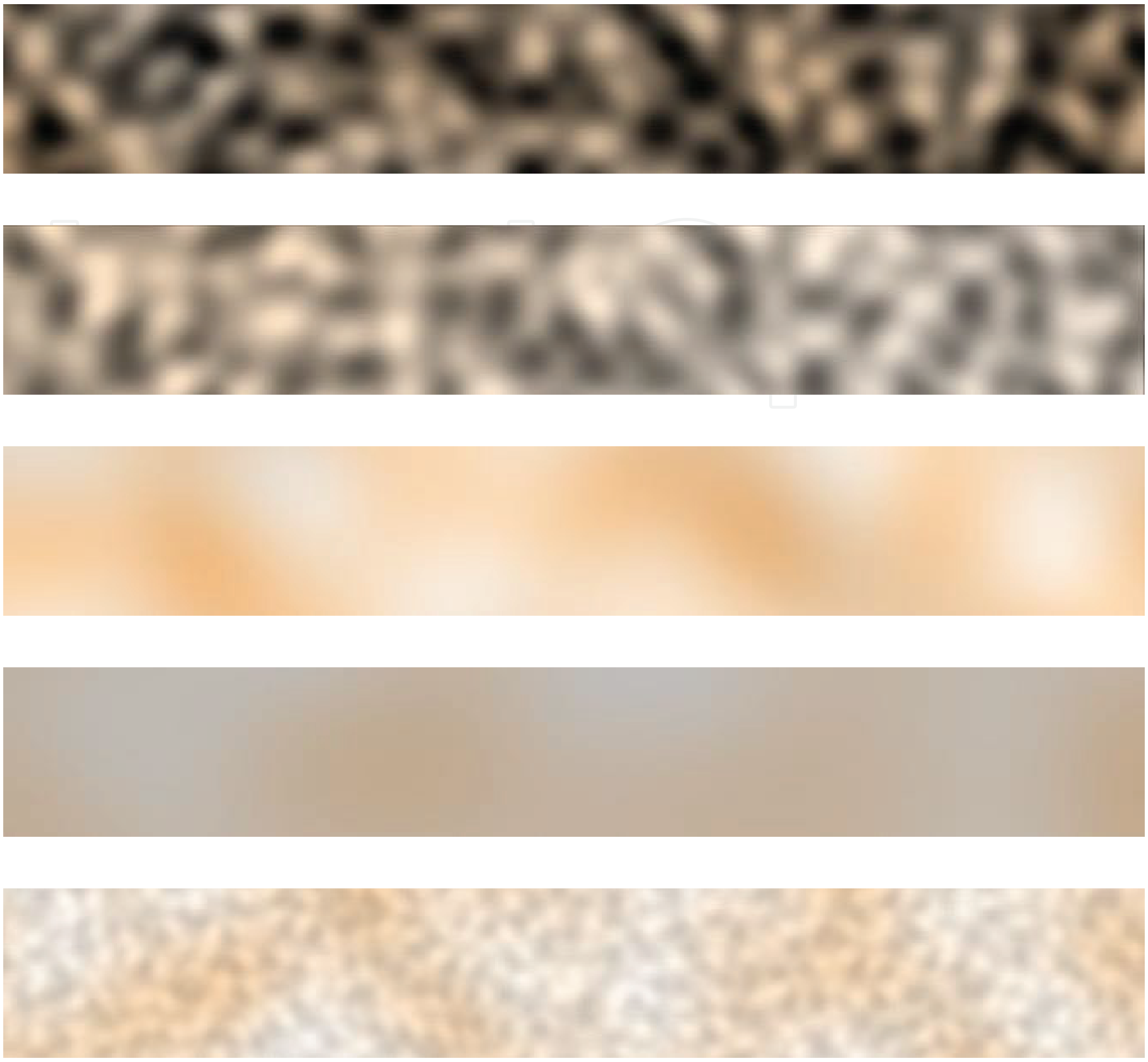

Figure 6. Instances of the digital weather procedural generator. The sliders through iterative tests have been adjusted to output dynamic imagery within a scope relevant for the Observational Instrument to produce lighting variations and dynamics similar to the influx of daylight.

investigation of subtle relationships of difference, which produce experiences of couplings between the two light domains as to which is foregrounded or backgrounded as organising texture. The design of the procedural software generator in digital weather delivers the exact same output, the exact same lighting formation given the same input on the sliders. The particular output is linked to the absolute time the software runs, so when the time of the particular moment is replayed, the software produces an exact duplicate lighting dynamics. This absolute time dependence allows the replay of events, reverse replay of events, and replay in any scaling of time as well as range, speed, and spread of the output. The organisation of the procedural software generator, which enables asynchronous and adjusted parameters, produces a design opportunity for detailed adjustments on scenarios recoded through experiential investigations. Further, an opportunity is created to delicately design lighting scenarios for aesthetic preferences or organised according to practical needs.

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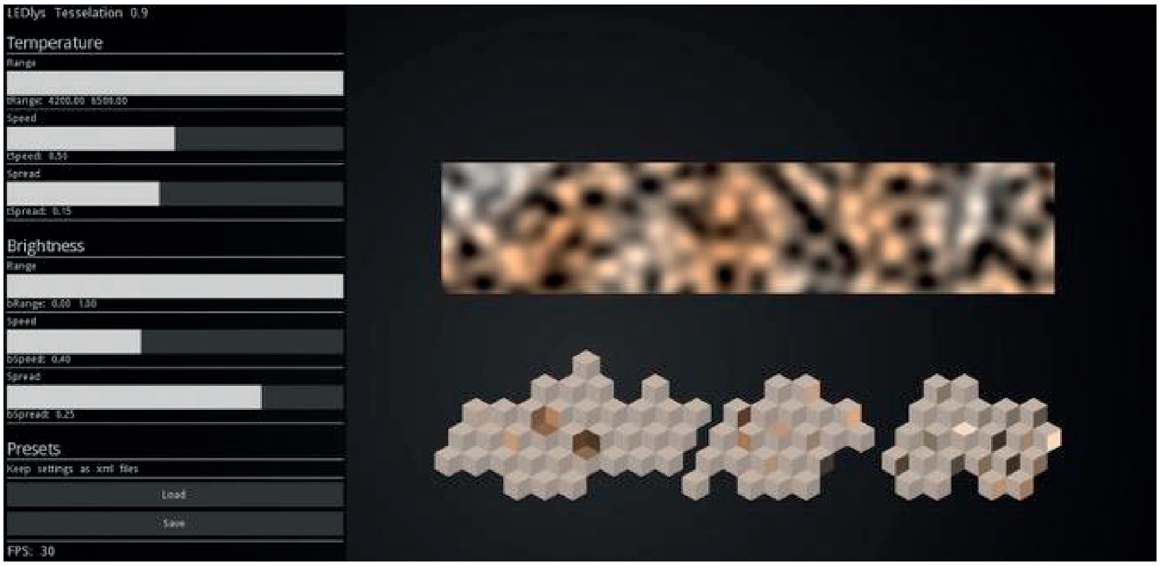

Figure 7. The control interface of the digital weather system shows exactly how the generative software produces a dynamic cloud texture, which then is mapped upon an image of the instrument. The back-lit surfaces of the instrument are adjusted accordingly. The sliders on the left help in adjusting the software parameters. The texture generation occurs in two separate layers: temperature and brightness, which control the colour temperature and the luminous intensities, respectively. Pre-sets can be saved and reloaded to allow for comparison across time and enable the development of sets of reference setting. One of the most interesting aspect of the Observational Instrument is to observe the most minute variations between artificial and natural light, an almost seamless integration, and thus enable a deeper and expanded experience of ambient relations, which then becomes possible to observe. Through the delicacy of the interweaving of fluctuations, the integrated lighting appearances become a separate quality in architectural lighting design, in ways that possibly enhances the material ambient qualities of architectural space.

Figure 8. Integrated daylighting and artificial lighting. A close look at a section of the instrument where some surfaces are lit by daylight and some by the embedded LED. The surfaces appear in a range of lit, reflected, and shadowed showing the range of local light variations. **Figure 9** shows the same section with the curtains drawn for the window, excluding the daylight.

5. The design of the Observational Instrument

The physical setup of quadratic surfaces is constructed to reflect incoming daylight, has a clear readability of shadows and light, and enables compositions of artificial light from a subset of surfaces with integrated LEDs. The surfaces are made of semi-transparent acrylic with frosted surfaces, and they are in this way able to merge light from the LEDs emitting from the inside with daylight reflected on the surface from the outside. The aim is to have a structure for experiencing compositions of fluctuating artificial light integrated with natural variations of daylight. Each light-emitting surface is outfitted with a reflector and a piece of LED strip with high colour rendering indices (CRI) warm white and cold white LEDs. The embedded LED strips are driven from LED drivers that are capable of operating with a bit depth of 16, giving a fine-grained control of intensities with more than 65,000 digital steps, effectively making fine and slow intensity shifts almost imperceptible. With the usual bit depth of 8, we would have experienced discrete digital quantisation in slow intensity fluctuations, especially in the lower 10% range, where a range of 256 steps becomes very visible. Dimming curves are adjusted to perceptual dynamics, with much higher resolution in the darker range than in the brighter one and further adjusted to enable smooth transition through the Kelvin scale.

5.1. Intensity and colour temperature

The built-in luminaires have two variables, luminous intensity and colour temperature. These two variables can fluctuate completely independently, as our LED lights decouple the relationship between colour temperature and luminous intensity that was interlocked in incandescent bulbs. The variables form a two-dimensional space of possible light outputs. Any point in this space can describe the current state of a single light emitter. The lightness could be experienced as bright, dim, off, blinding, etc. The colour temperature could be warm, cold, etc.

5.2. Time and durational composition

Fluctuations occur over time, and we are interested how fluctuations affect our experience of artificial light. The fluctuations are our path through intensity and colour temperature. How does the experience of the fluctuations change with their speed and what is the relationship between speed of light fluctuations to its integration and adaption as artificial light to the daylight influx?

If colour temperature and intensity describes the 'what' of our light emitter, the fluctuations describe the 'how'. Fluctuations can have temporal qualities such as repetition, rhythm, syncopation, flicker, etc. We would like our light compositions to potentially exhibit all of these complex qualities, without having to expose a plethora of parameters and options in the software interface.

With LED lighting, any change in intensity or colour temperature can occur discretely or continuously, that is, at an instant or gradually over time. However, we are mostly interested in exploring artificial lighting fluctuations that are reminiscent of natural phenomena. As nothing moves physically in zero time, we want the fluctuations to appear continuous. We look for

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a simple function that allows us to generate fluctuations that are continuous at low frequencies and appear unpredictable yet subtle. The function should have sets of time variables, and the user should be able to control the speed of this time. The core driver of fluctuations over time is the Perlin Noise animations, which generate a form of pseudo-random coherent noise that has proven useful for procedural generation of seemingly natural structures. When interpreted as light fluctuations over time, the Perlin Noise exhibits qualities ranging from imperceptible, alive, over syncopated to noisy.

5.3. Spatial composition of light fluctuations

A major visual component of LED lighting is the possibility to individually control light emitters. Let us now look at a collective of lights. When more lights are arranged together, their fluctuations collectively assume relative spatial qualities such as dense, sparse, coarse, uniform, and individual. When taking part in such an arrangement, a light emitter can be interpreted as a pixel.

If the coherence takes the form of figurative representation, it is reminiscent of the effect of mapping the spatial relationships of the lights to a video input. However, our focus is on the experience on spatial and temporal qualities that lies beneath concretely representational uses of lights as pixels, towards signals that give our lights a spatial relationship. For this abstract spatial reference, we use Perlin Noise in two dimensions, which could look like the one in **Figure 9**:

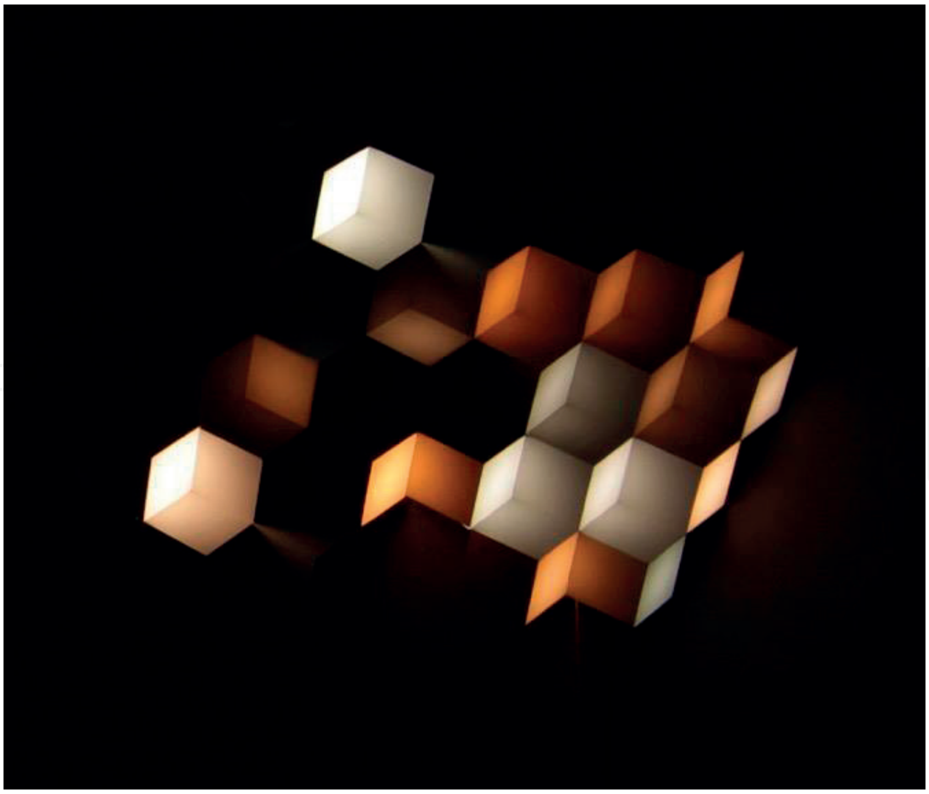

Figure 9. The artificial lighting as it looks when the curtains are drawn excluding the daylight influx. **Figure 8** presents the instrument with both daylight and embedded artificial light.

5.4. The control of adaptive lighting dynamics

With an outset in the principles of using generatively animated two-dimensional Perlin Noise as a source for colour temperature and luminous intensity, a control software has been developed that enables the designers to generatively synthesise, study, and describe temporal and spatial qualities of fluctuating light compositions. This cloud of Perlin Noise would be animated over time, at a user-defined speed. The image at the top of the screen is a composite of the two animated Perlin clouds. This animation is sampled and mapped onto the individual light-emitting surfaces that are shown in the visualisation of the Observational Instrument. The mapping retains the spatial relationship from the image to the arrangement of lights. (**Figure 10**).

There are two similar-looking sections for 'Temperature' and 'Brightness' and a bottom section for loading and saving pre-sets. The two sections for Temperature and Brightness each have three parameters that control how their Perlin Noise animation behaves. The first parameter is manipulated with a Range slider that sets two values: the minimum and maximum for the fluctuation. This means the white portion of the slider can be dragged sideways at both ends, effectively contracting or expanding the possible range of intensities of temperatures. The range slider is linear.

The middle slider sets the Speed of the fluctuation. This slider is cubic, prioritising high resolution in the lower (slow) end of the scale. A cubic slider allows for finely tuning extreme slowness, an important prerequisite for composing fluctuations that are changing at an almost imperceptible pace. On the other hand, the slider will still allow extremely fast fluctuations at the higher end of the scale, allowing comparative experiential research of the extremes. When at zero, the animation is stopped.

The last slider sets the so-called Spread of the cloud. This is effectively a 'zoom' slider allowing scaling of the Perlin Noise. This can be understood as 'how far the lights are from each other' or 'a scale between uniformity and individuality'. When at zero, the Spread parameter generates an animation that is 1x1 pixel, rendering a uniform value across the noise field, in effect letting the lights behave in unison. When dialled all the way up, the Spread parameter generates an animation that is very fine-grained, in effect letting the lights behave totally individual without any apparent coherence (**Figure 12**).

Figure 10. A two-dimensional Perlin Noise field at a given frequency: spread or zoom-level.

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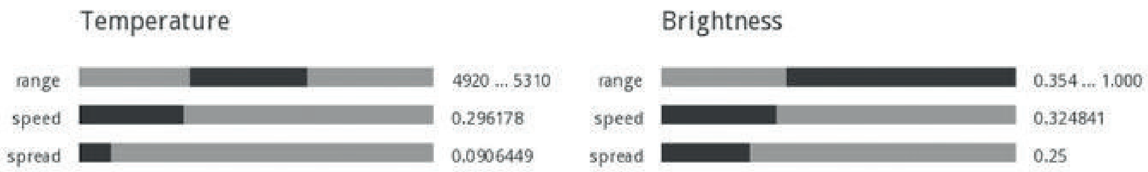

Figure 11. Digital weather animation controls.

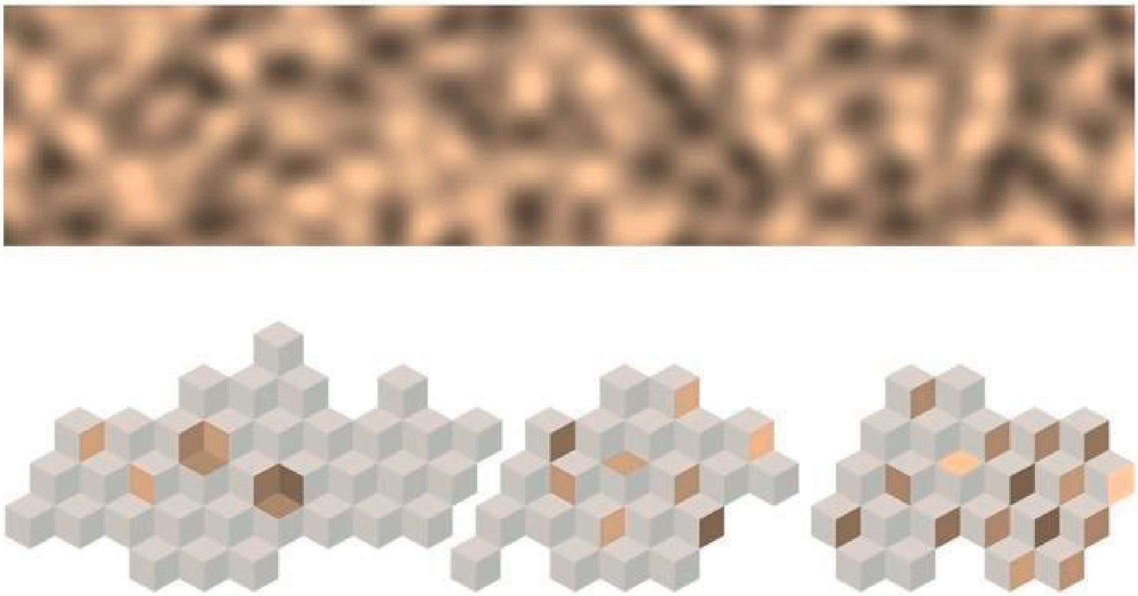

Figure 12. The digital weather animation and the mapping onto the Observational Instrument.

Remember that this is an animated noise: generative and continuous. When formatted as light output in the Observational Instrument, it is possible to synthesise abstract lighting fluctuations that are reminiscent of the fluctuations in natural daylight as weather fluctuations, reflected light from water surfaces, filtered light from the movement of leaves in trees, or modulated light variations by the passing of clouds (**Figure 11**). Other more extreme or 'unnatural' compositions are also possible, and allow for comparatively studying and qualifying the temporal aesthetics of dynamic artificial light interplaying with the always-dynamic daylight.

Engaging with the Observational Instrument and tuning between daylight and artificial lighting enables the development of enhanced sensibilities to minute nuances in the light fluctuation. The Observational Instrument stages an experiential situation where experience of delicate adaptive lighting dynamics can be rehearsed and tested, progressively building a refined capacity to understand and design with lighting dynamics.

6. Engagement with lighting design experts

The integrated weather systems focus on change and variation and promote an expanded field of dynamic flux in the artificial lighting. The appearance of adaptive dynamics as ambient flux might also allow a new form of entanglement of user experience, which involves a dynamic overlap between the dynamics of visual impressions and perceptual processes that emerge out of actions [9]. Ambience in this thinking is the experience of light fluctuations integrated as context, as an emergent material quality in-between several environmental influences [14, 15].

Fourteen architectural lighting design professionals have visited the installation in 2014 during the development phase and first iteration of the Observational Instrument, advising in the parameterisation and dynamics of the instrument. Each visitor spent 60 minutes closely observing the installation (**Figure 1**) guided through a pre-defined schedule of activities and engaged in continuous discussion as a semi-structured interview. The investigation followed three phases, where the visitors focused on: (1) the experience of lighting dynamics, (2) the integration with daylight dynamics, and (3) the perceptual experience of moving through the space themselves [16, 17]. The responses were rich and contextualised with in-depth expert knowledge on the challenges in the field, but a few significant positions can be extracted and synthesised.

The dual dynamics of the integrated daylighting and artificial lighting enables movement and changes the designers' focus from light as designed objects in space towards a form of ambient composition, which could be rehearsed in a range of variations through engagement with the instrument. The visitors noted the obvious capacity to enhance the daylight dynamics further into space, maintaining the textual and ambient qualities often missed in current system designs. The embedded Digital Weather algorithms seemed to show the ability to deliver daylighting qualities in spaces with no daylight access, enabling a relevant lighting design service in IoT infrastructures. The strategic move from lighting design as a configuration of luminaires that each contribute to the light in space, towards lighting as an embedded feature in the reflective materials of walls and objects, possibly with no primary light sources at all, would prioritise the architectural shapes as primary light givers rather than luminaires, and thus change the basic assumption on the elements that compose a lighting design.

The implications of the enhanced design capacities rehearsed by experiential engagement with the Observational Instrument have relevance in several contexts of lighting design. The possibility of adaptive lighting enables heightened focus on the need for daylight exposure when indoor facilitates enhanced relation between dynamic outdoor condition in the indoor environment and promotes energy saving by using more daylight and less artificial lighting. The delicate adaptive artificial lighting allows architectural designs beyond the current constraints, where the design solution facilitates a common average of daylight influx, often leading to measures of shading to keep the daylighting dynamics in control. With a dynamic integration of daylight and artificial lighting, more daylight can be allowed to enter indoor, delicately controlled by adaption of lighting conditions across the day, and weather conditions.

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design and descriptions of the software functions and interface design were done by Ole Kristensen, ITU. The project is described in detail in the published report: An Exploration into Integrating Daylight and Artificial Light via an Observational Instrument [18].

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