An Experiment in Virtual Reality to Measure Daylight-Driven Interest in Rendered Architectural Scenes

Siobhan Rockcastle[1], Kynthia Chamilothori[1], Marilyne Andersen[1]
[1]Laboratory of Integrated Performance in Design (LIPID), École polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland
siobhan.rockcastle@epfl.ch

Abstract

This paper introduces an experiment using a virtual reality headset to collect subjective evaluations of rendered daylit architectural scenes. By varying sky conditions and view directions from a fixed view position, the authors collected subjective perceptual ratings from architectural renderings and compared them to image-based measures related to impressions of visual interest. The use of virtual reality allowed for the extraction of headtracking data, providing additional insight on how people perceived the immersive scenes. Findings reveal a dependency between visual interest impressions and quantitative predictors, both of which vary with sky conditions and view directions within the scene.

Introduction

The perceptual qualities of daylight have been broadly acknowledged by the architecture profession to have profound impacts on our aesthetic and emotional judgement of space (Holl et al. 2011; Pallasmaa 2012; Steane and Steemers 2004). These impacts may be orchestrated by the designer to create a specific ambiance or range of visual qualities, but these qualities are often difficult to predict due to the highly dynamic nature of daylight. Research which attempts to identify, quantify, or predict perceptual impacts of daylight has been limited, in part due to the subjective nature of such assessments.

Human perceptions of daylight in space have been shown to be impacted by two dominant factors; mean luminance and luminance variation in the field of view (Veitch and Newsham 2000). Luminance variation in the field of view has been linked with evaluations of interest, in the work of Loe et al. (1994), as well as pleasantness, by Parpairi et al. (2002).

While most studies do not address the impacts of daylight distribution on an occupant's field of view, the Luminance Difference (LD) Index, as proposed by Parpairi et al. (2002), uses spatial measurements to quantify the luminance diversity across a range of view directions. Their findings revealed a relationship between higher measured luminous diversity and ratings of pleasantness by subjects within that view. Although it is a crucial step in our understanding of the perceptual effects of luminance variation, this method has practical limitations as it relies on physical measurements in real space.

To integrate knowledge about daylight distribution and its impact on the perception of the built environment, an objective measure and a simulation-based method for evaluation could help architects to compare design options. This would allow for the consideration of dynamic perceptual factors such as visual interest alongside performance metrics related to task illumination and comfort in the design development phase.

As a first step towards this, a novel set of metrics developed by the authors, Spatial Contrast (SC) and Luminance Variability (LV) and their annual cumulative representations, aimed to quantify the contrast and luminance variability in spatial as well as temporal terms (Rockcastle and Andersen 2014). Further development of this work, introduced in Rockcastle et al. (2016), used 2D renderings to collect subjective ratings of excitement in an online survey and developed a model to predict the distribution of responses using an image-based contrast algorithm and logistic regression model. The image-based algorithm, Modified Spatial Contrast (mSC), calculates local differences in brightness between neighboring pixels within an image. By sampling the image from a high resolution down to a mid-level resolution (1200 x 1200 to 75 x 75 pixels), the average difference between local neighborhoods is then computed and used to predict impressions of excitement (Appendix, eq.s 1-3). The mSC algorithm was adapted from a multi-level metric RAMMG, proposed by Rizzi et al. (2004) for computer vision (Appendix, eq. 4).

In a series of studies investigating the influence of presentation modes, Cauwerts et al. (2013) compared subjective ratings in real daylit environments and their corresponding virtual scenes in different projection modes. This comparison demonstrated that only the 2D panorama projection mode, where the user could explore the environment, was able to replicate the evaluation of *perceived pleasantness* and *light distribution* of a real space. The importance of *immersion* and *interactivity* within the virtual environment has been identified in various studies (Bishop and Rohrmann 2003; De Kort et al. 2003; Newsham et al. 2010). Virtual reality headsets have been suggested as a means to create a more immersive virtual environment (Kuliga et al. 2015) due to the lack of conflicting stimuli in the observer's peripheral vision.

To the authors' knowledge, very few studies have used a an immersive virtual reality display in the investigation of impressions of lighting. Heydarian et al. (2015a) demonstrated that user performance in object identification, reading speed and comprehension in an office space was similar in a real office environment and its virtual representation shown with the virtual reality headset Oculus Rift DK2. In a later experiment (2015b), Heydarian et al. explored the lighting preferences of users in a virtual scene through the users' control of the blinds and artificial lights in the virtual environment. A study by the authors, introduced in Chamilothori et al. (2016), used the same device to investigate the influence of façade patterns on the perceptual impressions of a simulated daylit space. Ongoing work by the authors (Chamilothori et al. 2017) compares the subjective evaluations of a real and a simulated daylit space in different lighting conditions. The results of this study are promising for the adequacy of the studied methodology as a substitute for real environments in the investigation of perceptual qualities of daylit spaces.

The immersion of the user in the virtual scene, the ability to collect head tracking data from users in that scene and the mobility and reproducibility of experiments offered by this technology were the main driving forces for the use of a virtual reality headset in this study. The selected device is a state-of-the art headset, the Oculus Rift CV1. This headset has a 110° field of view display, using OLED panels with a resolution of 1080×1200 pixels per eye and a refresh rate of 90 Hz. The maximum measured luminance of the display is 80 cd/m^2 for a white scene, RGB (255, 255, 255). As the display turns off to display black color RGB (0,0,0), resulting to a luminance of 0 cd/m^2, the next smallest measurement is 1 cd/m^2 for RGB (32,32,32). Although the maximum luminance of the display is expected to reach 300 cd/m^2, rather than 80 cd/m^2, this discrepancy is explained by the low persistence mode of the device, which turns the pixels off between frames to alleviate motion blur, resulting to a lower perceived luminance in the duration of a second.

The experiment and analysis presented in this paper transitions from a 2D rectangular to a visually immersive approach in all the studied aspects: image projection mode, imaged-based analysis and prediction model. Building upon the algorithm presented by Rockcastle et al. (2016), described in Appendix eq.s 1-3, we have adapted the mSC algorithm to a 360° environment-mapping image format to assess a semi-annual time series of 360° HDR renderings and select instances of maximum excitement as predicted by the algorithm. From these instances, the view directions with highest and lowest predicted excitement under clear and overcast skies are selected using the mSC algorithm and used to extract 180° scenes, each facing one of the selected view directions, so that we may study the impact of view and sky on subjective impression of visual interest within each space selected for the experiment. By showing subjects a selection of tonemapped 180° scenes, we will compare a range of view directions *within* a space and measure how impressions of visual interest vary *across* that space based on view direction and sky type.

The display of scenes in the Oculus CV1 headset allows the collection of subjective responses to qualitative daylight characteristics in a controlled immersive environment. Furthermore, head tracking data were collected from each session, providing the researchers with behavioural view patterns within each scene. Subjective ratings from subjects were compared to quantitative predictors to validate the use of image-based algorithms in predicting impressions of visual interest across space and over time.

Simulation Workflow

The following section introduces the selection of case studies and the creation of renderings used in our experiment. Eight architectural scenes, selected to represent a variety of interior daylight conditions, were modelled in Rhinoceros and rendered in Radiance to generate 360° HDR scenes across a 28 step semi-annual time series. Modified Spatial Contrast (mSC), an algorithm developed to predict visual interest in 2D renderings was then adapted to a 360° environment-mapping image format and applied to this set of rendered scenes to select instances of predicted high and low probability for perceived visual excitement, under clear and overcast sky conditions. The instances selected by the algorithm were then further analyzed to find which view directions would correspond to the highest and lowest predicted visual excitement within that 360° field of view. The 180° HDR Radiance renderings corresponding to these view directions were then tone-mapped and used to generate immersive virtual scenes projected in the Oculus Rift CV1 virtual reality headset.

Selection of Case Studies

For this experiment, a range of architectural spaces were selected based on their internal daylight composition, from direct and exaggerated sunlight penetration to diffuse and uniform daylight conditions. For the selection of spaces, the authors considered a range of conditions: daylight distribution (direct, diffuse, varied), architectural style, latitude, and program use. Regarding daylight composition, spaces were selected to cover a range of typically high and low contrast daylight conditions.

The final selection of spaces for this experiment is shown in Figure 1a. Spaces include the Douglas Residence by Richard Meier, the Serpentine Pavilion by Toyo Ito, the Ryerson Student Learning Center by Snohetta, the Spencertown Residence by Thomas Phifer, the Zollverein School of Management by SANAA, the Poli House by Pezo von Ellrichshausen, the Menil Gallery by Renzo Piano, and the First Unitarian Church by Louis Kahn. All of these spaces may be considered architecturally significant and while the authors wanted to look at case studies that cover a range of daylight design conditions, future work must also consider more normative examples that represent more commonly occupied building stock.

360° HDR Renderings

All selected case studies were modelled in Rhinoceros to a consistent level of detail for structure, façade and fenestration components, interior partitions, and fixed elements such as railings. Removable interior artifacts such as furniture and lighting components were intentionally excluded to minimize elements that were not part of the built architecture. Material textures and fine surface details were also excluded to economize on modelling and rendering time, as a consistent rather than photorealistic level of detail was considered a priority by the research team. A central view position was established in each space, in equal distance from exterior walls (if possible, otherwise centered within a zone of the space) and at eye level (1.65 meters from the floor) to represent a human's perspective while standing. Geometry models were then exported as Radiance files using the DIVA-for-Rhino toolbar.

Material selections were made based on default reflectance values for wall, double glazed window, floor, ceiling, and fixed components, except where those elements were clearly higher or lower in reflectance, such as the Spencertown residence where surfaces are painted in the same high- reflectance paint. In this case, a 70 perent reflectance ceiling material was applied to all those elements uniformly.

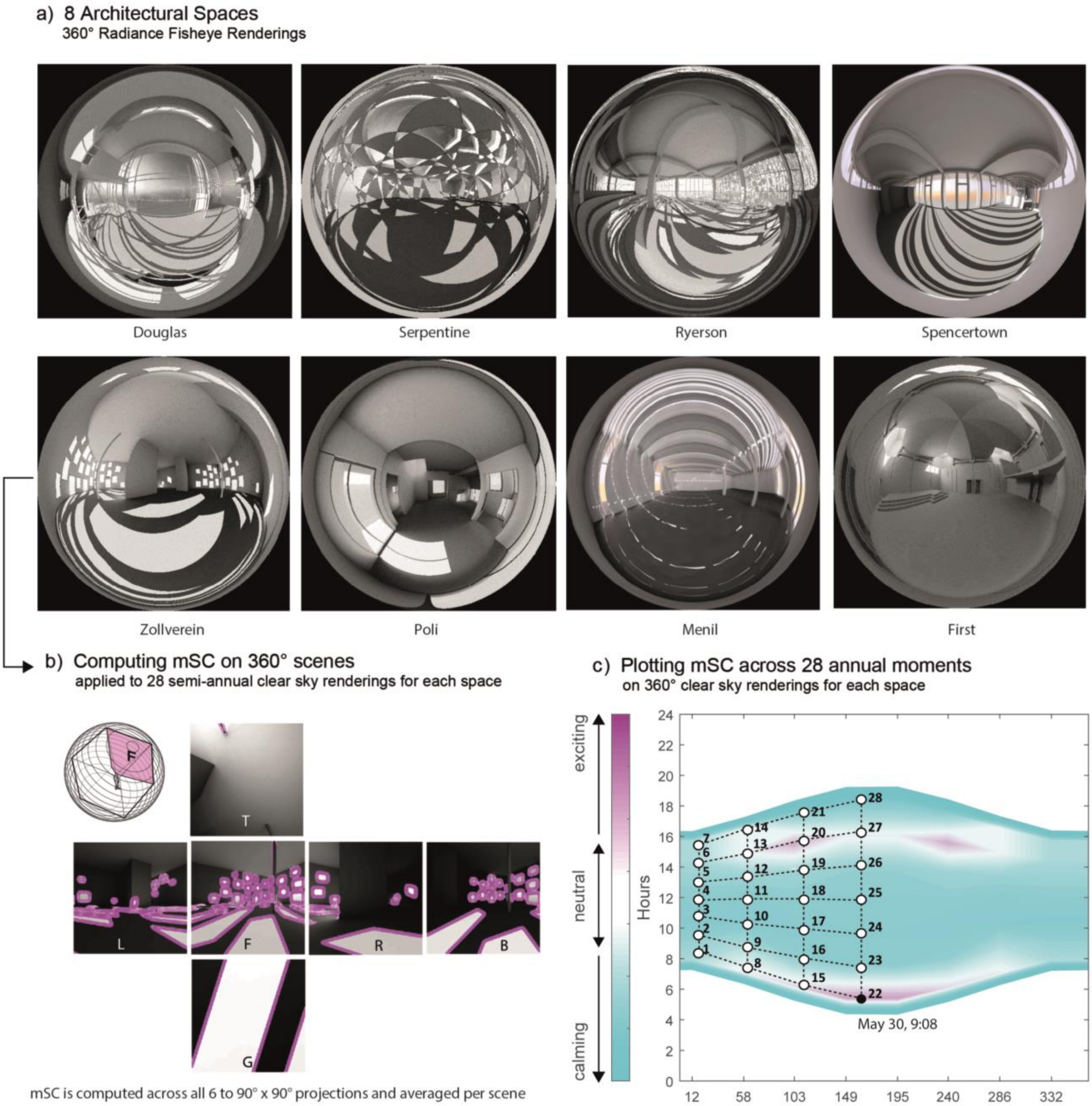

Figure 1 Showing a) the 8 studied architectural spaces, rendered as 360° tone-mapped angular fisheye renderings in Radiance, b) an adaptation of the mSC algorithm to find the average mSC across six 90° x 90° projections covering the entire 360° rendering and c) an annual plot showing the mSC results across all 28 semi-annual clear sky instances for one space, from which the instance of highest mSC is selected.

Table 1

a) Radiance parameters for first simulation phase, 28 semi-annual set (1-4 hours each)

dt	dj	ds	dc	dr	dp	st	ab	aa	ar	ad	as	lr	lw	pj	ps	pt
.05	0	.15	.75	3	512	.15	3	.1	512	4096	2048	8	.005	0	2	.05

b) Radiance parameters for second simulation phase, Oculus Rift rendering (12-48 hours each)

dt	dj	ds	dc	dr	dp	st	ab	aa	ar	ad	as	lr	lw	pj	ps
.05	0	.02	.75	3	512	.15	4	.025	512	4096	1024	8	1e-9	0	1

The selected architectural case studies were rendered in two phases using the Radiance lighting simulation software, developed by Ward Larson (1994). In the first phase, each scene was rendered at an intermediate level of accuracy across 28 symmetrical semi-annual instances (Figure 1b) under clear sky conditions using a 360° angular fisheye view projection (*-vta*). These 28 moments were adopted from the Lightsolve method developed by Kleindienst et al. (2008), where 56 full-year instances were shown to provide an adequate time series for interpolating daily and seasonal changes in daylight. As the authors are simulating both clear and overcast conditions, the symmetrical path of the sun allows us to get a representative series of moments from only half the instances. In the second phase, a selection of instances were rendered at a high level of accuracy under clear and overcast conditions.

To select the moments to be renderd in the second phase, each of the 28 angular fisheye renderings produced using intermediate parameters (Table 1a) was tone-mapped using the *pcond* algorithm, developed by Ward Larson et al. (1997), and a gamma correction of 2.2 based on the measured luminance range of the display. While the literature suggests that other tone-mapping operators may be perceived as more realistic, we decided to use *pcond* as its native adaptation in Radiance allows for a projection-based compression of luminance that could be applied to our angular fisheye image projections. Future work is needed to determine the impact of tonemapping operators on the perception of scenes in virtual reality.

The tone-mapped fisheye renderings were then transformed into a cubemap projection using the function *pinterp*, resulting to six 90° x 90° perspective renderings, each corresponding to 1/6th of the full scene. This set of renderings, generated from the equivalent fisheye projections, were analysed in Matlab using an adapted algorithm developed to assess mSC across the two-dimensional faces of the cubemap projection. This adaptation of mSC has the advantage of not needing a pixel-based weighting, as it is applied directly to the perspective projection of each cube map face. As each face shares a virtual 'seam' with its neighbor (both top, bottom, left, and right), this algorithm was designed to address both edges and corners of the image. While conceptually straight forward, the implementation into a functional algorithm is shown in Figure 1b, where the cubemap projection is described as a set of related faces, with the edge of each face sharing pixel neighborhoods with adjacent faces. A critical point in this procedure is that the fisheye renderings were tone-mapped before the generation of the cubemap faces, as any compression of luminance values must be done consistently across the entire scene. If the faces are tone-mapped separately, seams between images become visible both in the virtual scene and in the application of mSC, creating contrast boundaries that do no exist within the scene.

From the application of mSC on this time series of cubemap projections, the instance with highest mSC was identified as shown in Figure 1c and re-rendered with high precision Radiance parameters for clear and overcast sky conditions for each of the studied spaces (Table 1b).

Hemispherical View Directions

An additional step in the simulation workflow was required in order to select the view directions with the highest and lowest prediction of visual interest within each scene, as described below. For each instance of clear and overcast skies rendered for the Oculus, the mSC algorithm was applied to a series of 18 hemispherical (180°) angular fisheye projections, generated using the Radiance function *pinterp* in 20° radial increments as shown in Figure 2. The resulting 180° angular renderings were analysed separately with the mSC algorithm, this time using an adaptation for hemispherical image formats, to select the highest and lowest measures of mSC in each view direction (VD) and sky condition. This resulted in four variations of each space: a) clear sky under highest mSC VD, b) clear sky under lowest mSC VD, c) overcast sky under highest mSC VD and d) overcast sky under lowest mSC VD.

Projection of Final Scenes

In order to project the final rendered scenes in Oculus, the authors used a workflow developed for the generation of immersive scenes (Chamilothori et al. 2017). The scenes are created in the game engine Unity using each set of six perspective renderings and the principle of cubemap projection, which gives a seamless impression of immersion to the scene observer. Although the projected images were not stereoscopic, as the same image was projected to both eyes, the loss of 3D object perception was minimal due to the scale of each scene. Stereoscopic projection is most critical in scenes with objects close to the foreground of the observer. In addition to visual immersion, the virtual scenes projected in Oculus allow for the collection of head-tracking data in each experimental session. This data allows for the analysis of recorded view behaviour within the different scenes and conditions.

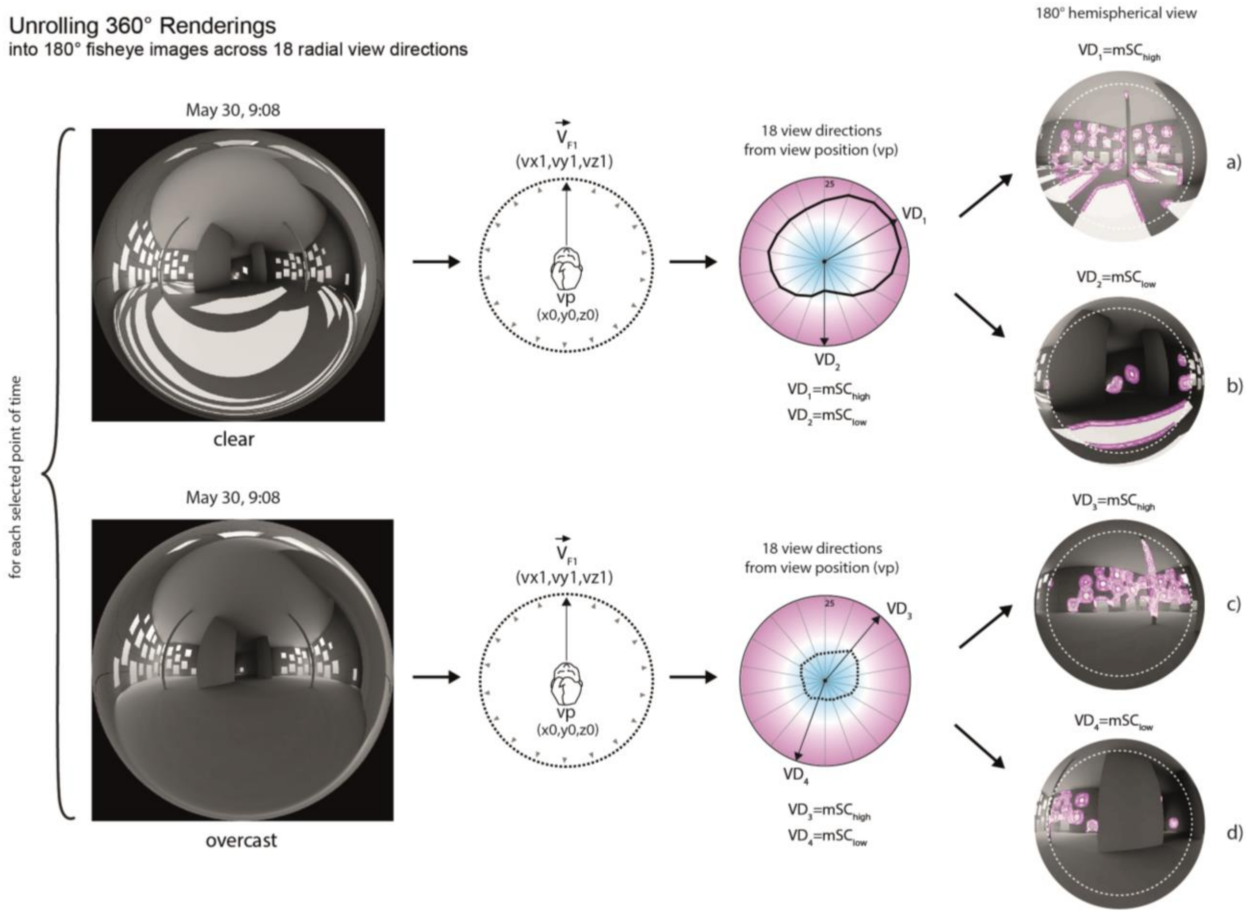

Figure 2 For each selected instance shown in Figure 1a, clear and overcast sky conditions were re-rendered using more accurate Radiance parameters. From these 360° scenes, the authors generated a series of 18 angular fisheye renderings, (180°), varying the view direction in 20° radial increments. Using the mSC algorithm adapted for a 180° angular fisheye projection, each view direction was independently analyzed for predicted excitement and the high and low view direction were selected for each sky condition.

Experimental Design & Procedure

This section will describe the experimental design used in our study, followed by the collection of subjective responses to qualitative daylight characteristics from participants immersed in the projected scenes.

Design of Experiment

For this experiment, we used a fully randomized presentation of spaces and sky conditions/view directions. While each subject saw all eight architectural spaces (Douglas, Serpentine, Ryerson, Spencertown, Zollverein, Poli, Menil, and First, Figure 1a), the spaces were presented to subjects under a randomized set of conditions, corresponding to one of four possible sky and view combinations, as determined in subsection 'Hemispherical View Directions.'

Because the participants were only able to explore half the overall scene, we expected their impressions to vary depending on view direction. Having subjective data on specific view directions allows us to understand how impressions of interest vary across the visual field based on localized architectural characteristics.

Using a 10-point unipolar scale with verbal anchors at the ends of the scale (1 - not at all, 10 – very), the subjects were asked to rate how pleasant, interesting, exciting and calming was the space and how diffuse and contrasted was the light in the space. These words were selected from two previous studies conducted by the research group (Chamilothori et al. 2016; Rockcastle et al. 2016).

Subjects & Experimental Procedure

This virtual reality experiment was conducted at EPFL in October, 2016 over the course of three weeks. Subjects were unpaid volunteers who were recruited via email, social media and posters. The study took place in different seminar rooms around the EPFL campus as the semi-portable nature of this experiment allowed for easy set-up and access a larger population than a fixed lab experiment. The experimental equipment included the Oculus Rift CV1 and an Acer Predator 17-X laptop, capable of supporting the VR headset. Subjects were between 18 and 50 years of age with a mean age of 29 (std=5.7 years, 30% female and 70% male) and were screened for English language capacity; eligible participants had a English proficiency of C1 or higher.

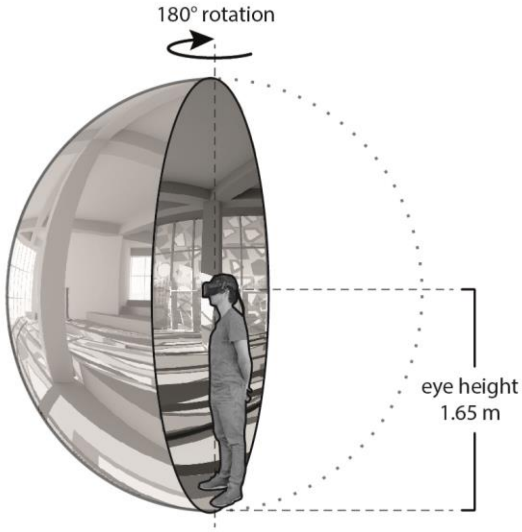

Figure 3 Illustration of the participant's perception of the 180° immersive scene in virtual reality.

They were asked to wear contact lenses or glasses, if needed, to ensure visual acuity. A total of 65 subjects participated in this study, with a minimum of 15 subjects per space and sky/view combination.

Each experimental session lasted roughly 20 minutes. Upon arriving for their scheduled appointment in one of the seminar rooms, subjects were asked to read an information sheet about the experiment and sign a consent form regarding their voluntary participation. After this step, they were asked to respond to a series of demographic questions. From there, subjects were asked to wear the virtual reality headset and adjust its fit in a training scene with the help of the researcher. They were told that the scenes they would see correspond a field of view of 180° and that they could turn around, standing in a fixed position, to explore the space within these boundaries. This ensured that the scenes were perceived as immersive, although corresponding to hemispheres, as long as the participants rotated within these boundaries (Figure 3).

When they were ready, the participants were presented with each of the eight rendered spaces in randomized order, in one of four possible combinations of sky and view direction. After freely exploring the immersive environment, subjects were asked to verbally respond to a series of ten-point unipolar scales on perceived characteristics in each scene. The order of presentation of the spaces was random, automatically dictated from the questionnaire and controlled by the researcher with the laptop's keyboard. After each session, the researchers collected head tracking data from the VR headset that could later be analysed for each participant and scene.

Analysis of Results

The following section of results will be presented in three parts. First, we look at the distribution of subject responses from each 180° scene for a selection of rating scales; *pleasant, interesting, and exciting*. As we were interested in creating a composite rating for visual interest, we also took the median value for ratings of pleasant, interesting, and exciting, hereafter referred to as 'PIE,' and considered it alongside the other unipolar scales. This preliminary composite rating does not include any attribute weights and is included as more as a proof-of-concept towards a composite visual interest rating. Second, we introduce the results from a non-parametric pair-wise comparison to present the effect of space and parameters on each ratings scale individually. Third, we investigate the relationship between subjective ratings and model predictors such as mSC, alongside other related algorithms, to see if they can predict responses from our immersive scenes. To this end, we apply a Pearson Correlation Coefficient fit between predictions from the selected metrics (SC, mSC, RAMMG, mean brightness and RMS contrast) and the median rating per scene (space, sky and view). Using the Pearson Correlation analysis to select best fits between ratings and metrics, we present the results of a logistic regression study between the composite rating 'PIE' and the RAMMG metric, which despite being very similar to mSC, showed a slightly lower deviance in goodness of fit.

Distribution of Subject Ratings

Figure 4 shows the distribution of subject responses for '*pleasant*,' '*interesting*,' '*exciting*,' and '*PIE'* for each of the 180° scenes, grouped by space, sky and view. Responses for ratings 1-5 are shown in a grey gradient while ratings 6-10 are shown in purple or pink. Ratings 8-10 are outlined in black to show the distribution of responses toward the high end of the selected scales. The measures of mSC, computed before the experiment, are listed above each of the 180° scenes. When we look at the distribution of PIE for Douglas, Ryerson, and Spencertown, the more asymmetrical spaces, we can see a shift in the distribution (if not always the median) between high and low view directions for both sky conditions.

Overall trends in distribution can tell us about the impacts of sky condition and view on visual impressions within each scene. As subjects were not aware which parameters we were testing, a noticeable shift in responses between sky conditions tells us that daylight does indeed have an impact on perception. Shifts in responses between view directions, from a fixed view position, also tell us that our interior view field could greatly affect our perception and appraisal of space, a somewhat intuitive finding, but one that could have impacts on spatial planning and design.

Effects of Space and Sky/View direction

A non-parametric Kruskal-Wallis pair-wise comparison was used to explore the effects of space and view/sky parameters on the distribution of responses for each rating (pleasant, interesting, exciting, calming, diffuse, contrasted, and 'PIE').

Figure 5 shows the mean value and distribution of responses for the 'PIE' rating, separated by the effects of sky and view (on the left) and space (on the right). While we can see a slight shift in the mean response for PIE when grouped by sky and view, the difference is not statistically significant.

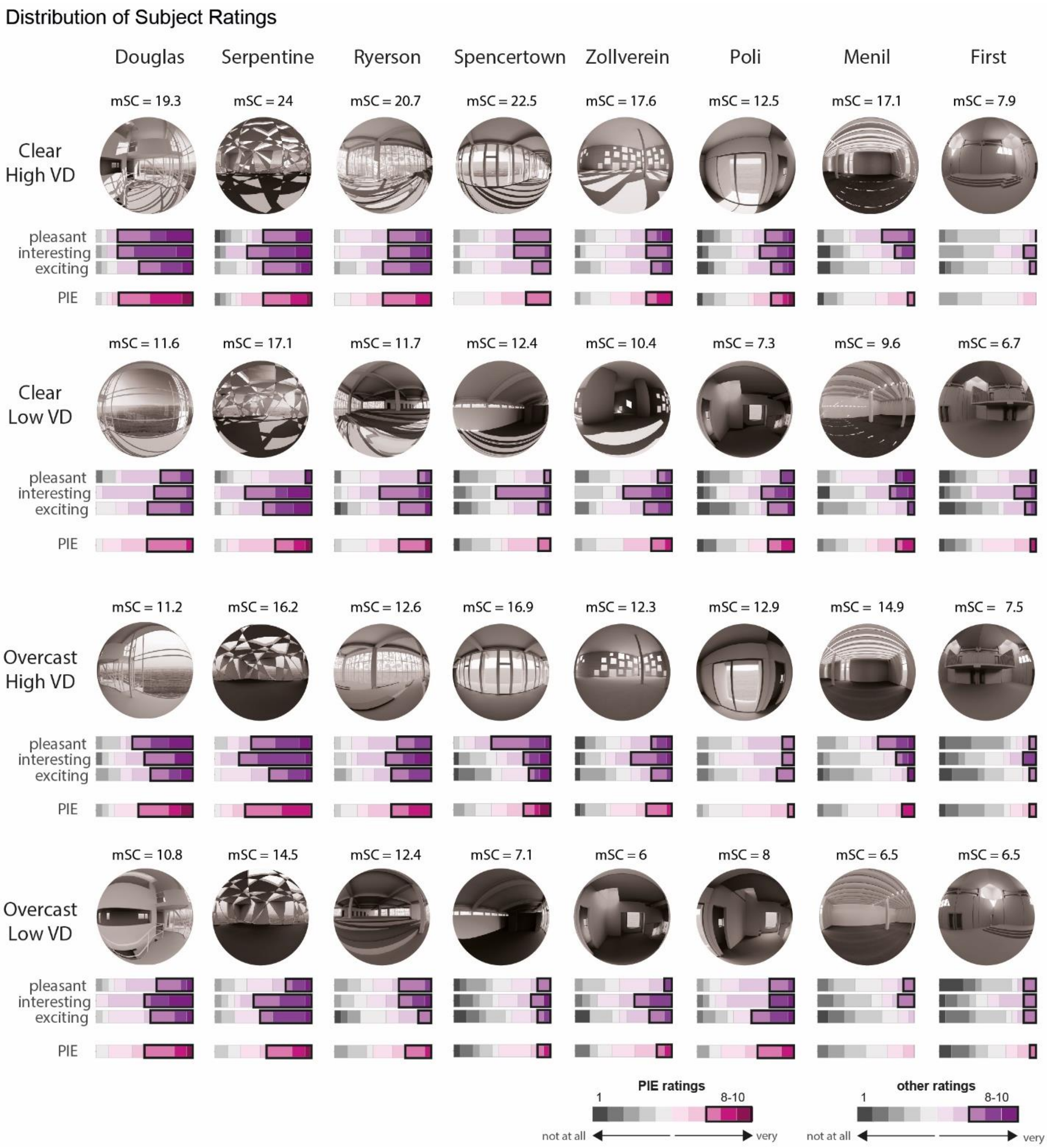

Figure 4 Distribution of subject ratings for '*pleasant,' 'interesting,'* and *'exciting'* for each of the 8 spaces and 4 sky/view conditions per space and view direction.

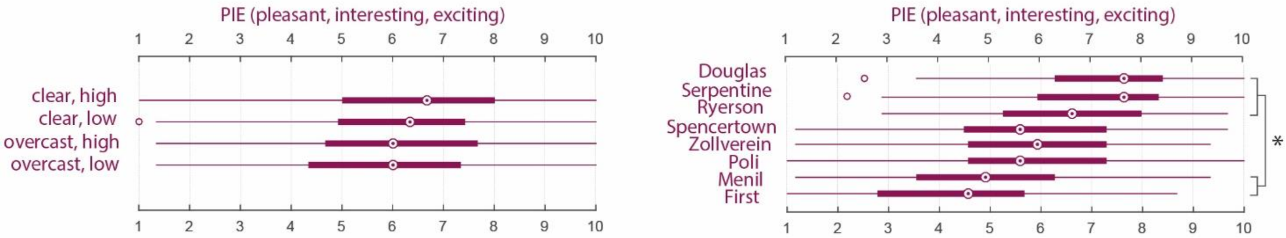

Figure 5 Kruskal Wallis pair wise comparisons for sky/view direction and space factors. The significant difference in mean rank between spaces is noted with "*", such as between Douglas/Serpentine/Ryerson and Menil/First.

This makes sense considering the fact that ratings for the clear/low view directions were often higher than the overcast/high and that this varied depending on architectural space. As such, view and sky alone did not always produce the highest conditions of pleasantness, interest, and/or excitement. The effects of space as an independent factor was, however, significant (<0.05) on mean 'PIE' ratings between the high cluster of spaces (Douglas, Serpentine, Ryerson) and the low cluster of spaces (Menil and First).

Pearson Correlation Coefficient

To compare subject responses to quantitative algorithms used to predict elements of contrast, visual interest, and brightness, a PCC analysis was done between median responses to each rating scale per scene and quantitative predictions, extracted from previous studies in Rockcastle et al. (2016). The RAMMG predictor (with a seven level average N=7, see Appendix, eq. 4) was the most highly correlated to ratings of 'pleasant' (PCC=0.65, p<0.001) and the composite 'PIE' rating (PCC=0.66, p<0.001), as shown in Fig. 6. The mSC predictor was also highly correlated to ratings of 'pleasant' (PCC=0.64, p<0.001) and the composite 'PIE' rating (PCC=0.63, p<0.001). Fits were also relatively strong through ratings of excitement and interest for both mSC and RAMMG. A linear fit through median ratings does not always represent a robust goodness of fit with ordinal data as the distribution and not only the median is important. It is nearly impossible to establish a threshold over which ratings can be simply high or low and a logistic approach is more appropriate when responses are collected on an ordinal scale.

As such, we used the PCC fits to look for the highest linear fits between ratings and predictive algorithms and then ran a logistic regression analysis (proportional odds) through both mSC and RAMMG predictors to find the fits with lowest deviance.

Logistic Regression Analysis

From the logistic regression analysis, we found that RAMMG produced the lowest deviance with mean composite PIE ratings (19.13). It should be noted, however, that the fit was nearly just as good when using mSC (19.29) and the high correlation between these predictors (PCC=0.96) makes them nearly interchangeable. Figure 6b shows the fit through ordinal distributions for each rendered scene using RAMMG. As can be seen in the data, an increase in the RAMMG predictor results in a higher percentage of subjects who would rate the scenes higher for the composite 'PIE.' In other words, as RAMMG increases, so too does the percentage of subjects who rated those images as more pleasant, interesting, and/or exciting.

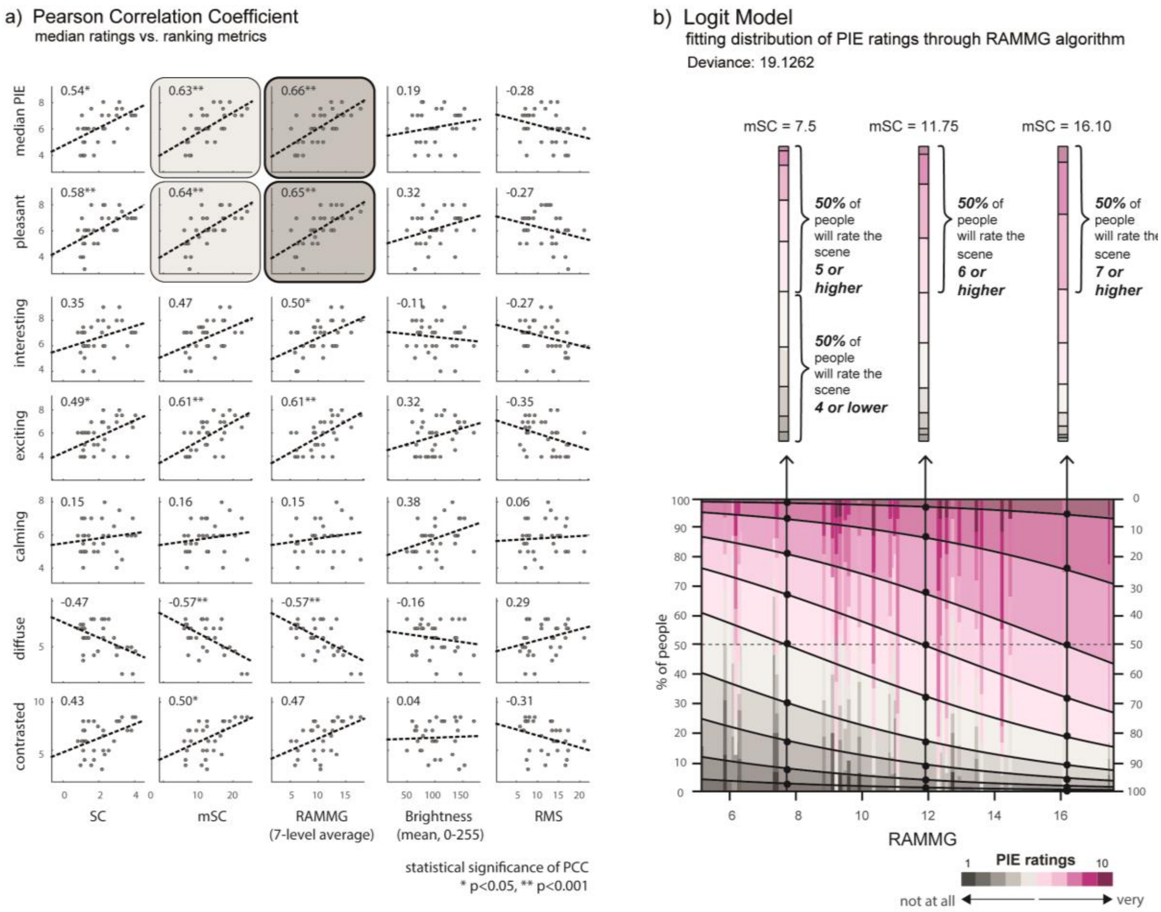

Figure 6 Showing a) PCC values between median ratings and quantitative predictors SC, mSC, RAMMG, mean brightness, and RMS b) logistic regression model fit through the PIE composite rating and RAMMG algorithm.

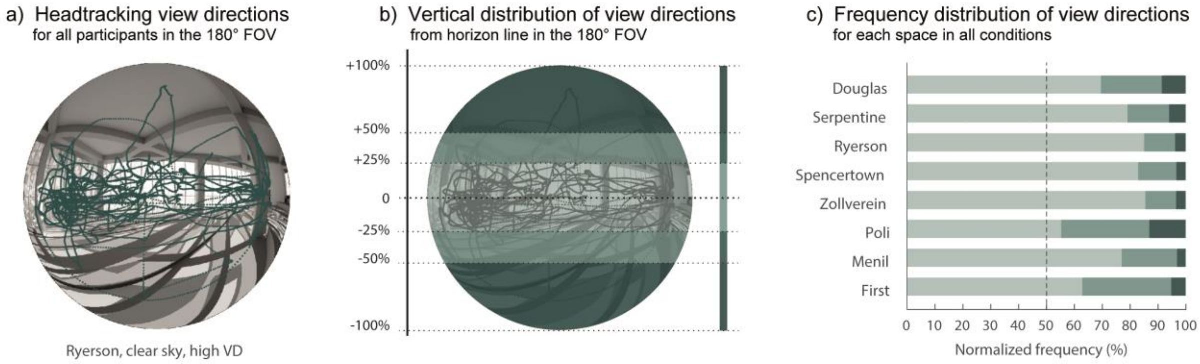

Figure 7 a) Headtracking view directions for Ryerson (clear sky, high VD) for all participants, b) grouping of vertical distribution of view directions and c) frequency distribution of view directions in the vertical axis for each space.

Head Tracking

As mentioned in the introduction, one of the main motivations for using VR in this experimental study was the ability to extract head tracking data, allowing us to see where subjects looked within each scene. While a more detailed analysis of this data is ongoing, this section will present a first overview of results that offer a possible explanation for variations between quantitative image predictors and subject ratings.

The collected head tracking data consists of a series of normalized vectors, generated every 11 milliseconds, from the centre of the headset in that instance. From this data, we extracted a series of head tracking view directions that corresponded to each space and sky/view combination for every experimental session, as shown in Figure 7a. These vectors were then separated into three groups based on their absolute vertical distance from the horizontal, expressed as a fraction of the vertical field of view: 0-25%, 25-50% and 50-100%, as illustrated in Figure 7b. By merging all the experimental sessions and conditions for each space, we calculated the normalized frequency distribution of the participants' vertical head movement in Figure 7c.

This analysis confirms an observation that was made by the research team during the experimental sessions: most of the time, the participants vertical head movement is within the 0-25% band of absolute distance from the horizontal. For all the spaces, on average, the head tracking vectors stay within the 0-25% band for 74.77% of the time, within the 26-50% band for 19.48% of the time and within the outer band for 5.74% of the time. The region between the horizontal and ±25% of the vertical field of view corresponds to 45°, which is in line with the suggestion of a 40° horizontal band as the main region of influence on perceptual impressions of space by Loe et al. (1994). This behavior could explain some discrepancies between the mSC-predicted excitement and the evaluation of the space, if the main interest-inducing source is outside of the focus of the users, as is the case with the roof of Menil, shown in Figure 4. Furthermore, this finding indicates that prediction algorithms could potentially be improved with the integration of a view dependent weight.

Conclusion

This paper introduced an experimental study using immersive 180° scenes from Radiance renderings of daylit architecture in the Oculus Rift CV1 headset. The authors collected subjective and objective data, through verbal questionnaires and head tracking respectively, introducing a novel experimental approach for use in qualitative lighting research. By varying sky conditions and view direction of rendered scenes within a population of subjects, the authors were able to compare subjective ratings of those scenes to quantitative algorithms designed to predict impressions of visual interest in a subject's field of view. While previous studies have used 2D rectangular images (from a single view direction) to predict impressions of excitement, this is the first study of its kind to use an immersive virtual approach, allowing for the collection of data from a fixed position in space across a range of view directions for two sky conditions.

In this paper, we introduced a preliminary composite rating called 'PIE' from a selection of attributes in our experiment. The fit between subjective ratings and the image-based algorithms designed to predict them is proof-of-concept that impressions of pleasant, interest, and excitement can be anticipated in immersive scenes and that those predictions are sensitive to view direction. That being said, each individual attribute could also be independently evaluated and presented to architects to provide a set of layered perceptual responses.

The insights gained from our preliminary assessment of head-tracking data also suggest that a subjects' view behaviour should be accounted for in the development of future image-based prediction algorithms. These observations should be supported by future work exploring the use of eye-tracking data, which could provide a finer-detailed analysis of view behaviour. The finding that subjects explored the 180° scenes primarily within a 45° wide horizontal band, centred in the field of view, is enlightening when we consider *where* the impacts of daylight-driven visual interest may have the most impact in architectural design from an occupant perspective.

Future development of this immersive occupant-centric approach to predicting specific perceptual effects can help designers understand the dynamic impacts of daylight on subjective appraisals of space across space and over time. A larger sample of architectural spaces, subjects, and sky conditions is needed in future studies to further validate the generalizability of these measures across a broad range of spatial conditions and occupant backgrounds.

Acknowledgement

This paper acknowledges support from the Velux Stiftung Foundation under grants 936 & 1022. The authors would also like to thank Dr.-Ing. Jan Wienold for his technical support in the preparation of Radiance renderings.

References

Bishop, I. and B. Rohrmann (2003). Subjective responses to simulated and real environments: a comparison. *Landscape Urban Plan. 65* (4), 261–277.

Cauwerts, C. (2013). *Influence of presentation modes on visual perceptions of daylit spaces*. (Doctoral Dissertation). Louvain, Université catholique de Louvain.

Chamilothori, K., Wienold, J. and M. Andersen (2017). Adequacy of immersive virtual reality for the perception of daylit spaces: comparison of real and virtual environments. *Leukos*, submitted.

Chamilothori, K., Wienold, J. and M. Andersen (2016). Daylight patterns as a means to influence the spatial ambiance: a preliminary study. In: Proceedings of the 3rd International Congress on Ambiances, Volos, Greece, 21-24 September, 117–122.

Charton, V. (2002). *Etude comparative de la perception d'ambiances lumineuses en milieu réel et en milieu virtuel*. (Doctoral Dissertation). Lyon, Institut National des Sciences Appliquées de Lyon.

Heydarian, A., Carneiro, J.P., Gerber, D., Becerik-Gerber, B., Hayes, T. and W. Wood (2015a). Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations. *Automat. Constr. 54*, 116–126.

Heydarian, A., Pantazis, E., Carneiro, J.P., Gerber, D. and B. Becerik-Gerber (2015b). *Towards Understanding End-user Lighting Preferences in Office Spaces by Using Immersive Virtual Environments.* In: Proceedings of the 2015 International Workshop on Computing in Civil Engineering, Austin, Texas, 21-23 June, 2015.

Holl, S., Kwinter, S. and J. Safont-Tria (2011). *Color, Light, Time.* First edition. Müller, Lars.

Kleindienst, S., Bodart, M. and M. Andersen (2008). Graphical Representation of Climate-Based Daylight Performance to Support Architectural Design. *Leukos 5*, 39–61.

Kuliga, S.F, Thrash, T., Dalton, R.C. and C. Hölscher (2015). Virtual reality as an empirical research tool - Exploring user experience in a real building and a corresponding virtual model. *Comput. Environ. Urban. 54*, 363–375.

Loe, D.L., Mansfield, K.P. and E. Rowlands (1994). Appearance of lit environment and its relevance in lighting design: Experimental study. *Light. Res. Technol. 26* (3), 119–133.

Pallasmaa, J. (2012). *The Eyes of the Skin: Architecture and the Senses.* Third edition. Chichester, Wiley.

Parpairi, K., Baker, N.V., Steemers, K.A. and R. Compagnon (2002). The Luminance Differences index: a new indicator of user preferences in daylit spaces. *Light. Res. Technol. 34* (1), 53–66.

Rizzi, A., Algeri, T., Medeghini, G. and D. Marini (2004). *A proposal for contrast measure in digital images.* In: Conference on Colour in Graphics, Imaging, and Vision, Aachen, Germany, 5-8 April, 187–192.

Rockcastle, S., Amundadottir, M.L. and Andersen (2016). Contrast measures for predicting perceptual effects of daylight in architectural renderings. *Light. Res. Technol.*

Rockcastle, S. and M. Andersen (2014). Measuring the dynamics of contrast and daylight variability in architecture: A proof-of-concept methodology. *Build. Environ. 81*, 320–333.

Steane, M. A., and Steemers, K. (2004). Environmental Diversity in Architecture. *Environmental Diversity in Architecture*. Ed. M.A. Steemers, Ed. K. Steane. New York: Routledge.

Veitch, J.A. (2001) Psychological Processes Influencing Lighting Quality. *J. Illum. Eng. Soc. 30* (1), 124–140.

Ward Larson, G. (1994). *The RADIANCE lighting simulation and rendering system*. In: Proceedings of the 21st Annual Conference on Computer Graphics and Interactive Techniques, SIGGRAPH '94, New York, NY, USA, ACM, 459–472.

Ward Larson, G., Rushmeier, H. and C. Piatko (1997). A visibility matching tone reproduction operator for high dynamic range scenes. *IEEE Trans. Vis. Comput. Graph. 3* (4), 291–306.

Appendix

The modified spatial contrast (mSC) in the level N (N=5 in the study by Rockcastle et al, 2016) is defined as

$$mSC_N = \frac{1}{WH}\sum_{i=1}^{W_N}\sum_{j=1}^{H_N} c_{i,j}, \qquad (1)$$

where $W_N = W_{N-1}/2$ and $H_N = H_{N-1}/2$ are the width and height of the image at level N halved in each subsequent level. and $c_{i,j}$ is the contrast of each pixel, calculated as

$$c_{i,j} = \sum_{k\epsilon K_8} \alpha\left|p_{i,j} - p_k\right|, \qquad (2)$$

where pixels p_k are the 8 neighbouring pixels of $p_{i,j}$ and the weight α applied to each of the 8 surrounding pixels *k* is

$$\alpha = \frac{1}{4+2\sqrt{2}}\begin{bmatrix} \frac{\sqrt{2}}{2} & 1 & \frac{\sqrt{2}}{2} \\ 1 & & 1 \\ \frac{\sqrt{2}}{2} & 1 & \frac{\sqrt{2}}{2} \end{bmatrix}. \qquad (3)$$

This weight was taken from the original definition of RAMMG, a multi-level contrast algorithm proposed by Rizze at al, 2004,

$$RAMMG = \frac{1}{N}\sum_{i=1}^{N} mSC_N, \qquad (4)$$