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Systematic measurement of perceptual design qualities

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ABSTRACT

Implications of design decisions are hard to oversee for designers. This is the case in particular with respect to decisions, which influence perception related qualities of designs. Such qualities are for example visual openness, visual privacy, and spatial intimacy. They are difficult to measure because of their subjective and soft nature. Measurements of such qualities are important because they are basis for user-oriented, optimal decisions in architectural design. Existing attempts in the architectural domain to assess such qualities systematically are not based on suitable models of space perception. Their ability to assess perception aspects of designs is limited. In this paper a new real-time measurement system for design is presented, which is based on a computational model of visual space perception. Core method of the perception model is a new method of geometric analyses termed Random Direction Distance Sampling (RDDS). Core method of the measurement system is exponential averaging, which is a time-series analyses method from the domain of Signal Processing known as exponential averaging.

Keywords: spatial perception, computational perception modelling, computational design, design assessment, design measurements

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1. INTRODUCTION

Design is a complex process. This complexity stems from ill-defined, and time varying design requirements, as well as voluminous solution space. Design requirements generally include requirements for perceptual design qualities. Systematic assessment of such qualities is a traditional bottleneck in design, in particular in architecture and interior design. Such qualities are visual openness, visual privacy, spatial intimacy and geometric variance. Assessment of such qualities is imperative to evaluate the satisfaction of design requirements, which is an essential component in design optimization. Satisfaction assessment outcomes guide the search for optimal design solutions. Real-time provision of measurements is rather imperative to ensure efficient and effective optimality search, and to allow real-time adjustment of requirements in course of design. The central question addressed in this paper is the following.

How can perceptual qualities of designs be measured in real-time?

Existing attempts in the architectural domain to assess perceptual qualities are not based on suitable models of visual space perception. They are generally based on conventional computations of spatial component information such as relative amount of openings in spatial enclosures (Koile, 1997, Franz et. al, 2005). The methods in use are generally based on Isovist analyses or analyses of graph theoretic design representations (Hillier et al., 1984). Isovists, which were introduced by Benedict in 1979 (Benedict and Burnham, 1981), are polygons, which enclose the volume directly visible from a location within a space. In many applications they were further simplified to the horizontal slices of these volumes at eye-height. Using Isovists for spatial analyses, certain properties of visual space perception are strongly simplified or not considered at all. These properties are variance in the significance of spatial directions in the visual field, detailed analyses of the geometric variance in the spatial envelope, and transition conditions, such as motion of the perceiver or real-time modifications of the spatial environment during design. Graph theoretic design representations are representations of designs in which design elements are represented as nodes, which are linked with other nodes in a network structure. Graph properties, such as mean shortest path length, etc. can be identified. Such graph analyses results are considered to be correlated with certain perceptual qualities (Turner et al., 2001), however, graphs identify visible locations only indirectly, via a certain network grid, and not directly in terms of physical visibility. Both, Isovist and graph based approaches are not based on modelling the visual space perception process. Due to sensitivity of visual space perception regarding the constitution of the visual field, detailed geometric properties of space, as well as transitions conditions, their ability to assess perceptual design qualities is limited. Real-time provision of measurement outcomes is rather imperative due to sensitivity of optimality searches with respect to simultaneous availability of all relevant design assessment information. In this paper a new real-time measurement system for design is presented, which is based on a computational model of visual space perception. Before coming to the explanation of the perception model and the measurement system, firstly the perceptual qualities measured in this research are concisely defined as follows.

2. DEFINITIONS

2.1 Perceptual Qualities

Perceptual qualities, such as visual openness, visual privacy, and spatial intimacy are qualities inherent to a design, which influence the perception of the design product. They are inherent to the design, because their existence and constitution is immanently linked to the existence and constitution of the design. The inherence is valid provided that the geometric constitution of the design remains unchanged. Because they are inherent to a design, they can be assessed during the design in place of afterwards, and they can be verified afterwards if that would be so desired.

2.2 Visual Openness

Visual openness is an inherent quality of a design, which describes how much a design allows for visual perception of distant positions. In the following, firstly the definition of visual openness of a single geometric position in a design is given, secondly the visual openness of a design as a whole is defined. The visual openness of a position in a design describes, how much a design permits retrieval of visual data from distant positions. Generally, opaque elements, such as walls, columns, furniture, etc. prevent visual perception of distant positions. The visual openness of a design is combined visual openness information coming from visual openness assessments of a number of relevant positions in a design.

2.3 Visual Privacy

Privacy, in general, is the ability of an individual to govern availability of hid/her information. As an inherent quality of an architectural design, privacy indicates, how much a design enables government of availability of information. Information of concern, in context of architectural design, is primarily of acoustic and visual nature. Privacy in architecture is consequently including visual privacy and acoustic privacy. Visual privacy of a position in a design describes, how much a design prevents retrieval of visual data of that position from other positions in the design. Generally, opaque elements, such as walls, columns, furniture, etc. prevent visual data retrieval from positions in the environment surrounding the position. The visual privacy of a design is combined visual privacy information coming from visual privacy assessments of a number of relevant positions in a design.

2.4 Spatial Intimacy

Spatial intimacy is an inherent quality of a design. Spatial intimacy of a position in a design describes, how much that position is enclosed by nearby opaque objects. The spatial intimacy of a design is the combined spatial intimacy information coming from spatial intimacy assessments of a number of relevant positions in a design.

2.5 Geometric Variance

Perceptual geometric variance is defined here as the exponential average of the variance of perception samples, which are variance of geometric distance samples. The greater the variance of the perception samples, the greater the perceived geometric variance. As consequence of this definition, the geometry perceived as most simple is the interior of a sphere perceived from its centre position. An example of a space with a high perceived geometric variance is the centre of a treetop, where distances to individual opaque points strongly vary.

3. MODELLING VISUAL SPACE PERCEPTION

In line with Helmholtz' definition of vision as a form of unconscious inference, which is defined as a process of deriving probable interpretation for incomplete data (Wade, 2000), and Marr's definition of vision as a process of information processing and representation (Marr, 1982), visual space perception can be defined as the retrieval and processing of visual data from the environment surrounding a perceiver. It is assumed that distances of positions surrounding a perceiver can be obtained accurately by visual perception. Sufficient accuracy of visual distance retrieval under normal spatial circumstances, with a large number visual depth cues in the perceived environment is assumed. The perception model presented here is a cyclopean model, which means the visual apparatus is represented with a single geometric point. Essential perception task is continuous retrieval of distance-information coming from positions surrounding the perception position. This process is termed Random Direction Distance Sampling (RDDS) here. Initial motor of the model is continuous generation of sightlines in random directions. Three uniform random numbers are used as components of a 3-dimensional direction vector. The utilization of random vectors as source for the directions of the sightlines is imperative due to unpredictability of geometric constitution of the measured environment, in particular with respect to the scale of its geometric roughness. The vector components of the direction of each sightline are shaped by means of Gaussian shape filtering in the following form.

$$f(x) = \left(x_{source} + x_{mean}\right) \times \sqrt{x_{dev}} \tag{1}$$

By means of modifying the parameters of the Gaussian normal distribution, x_{mean} and x_{dev}, the visual field, that is the probabilistic distribution of the orientation in sightline generation, can be adjusted in real-time.

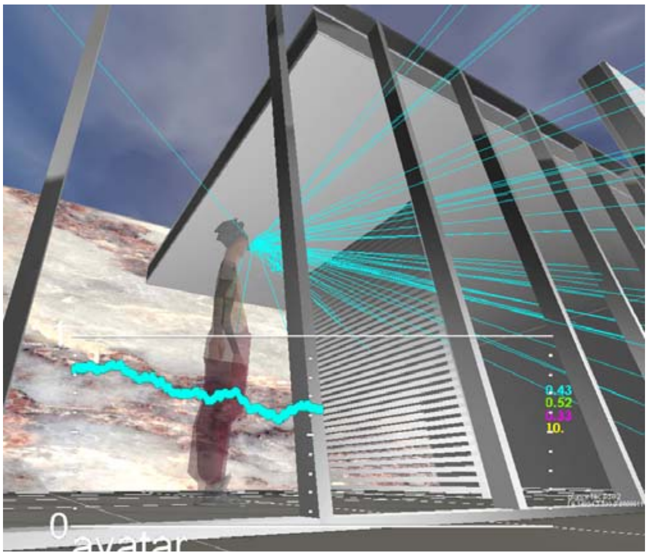

Figure1. Display of modelled visual space perception. Here the sightlines used to obtain the current measurement are shown, as well as the graph plot, which gives the measurement outcome.

A number of sightlines visually form a cone, with a greater density of sightlines in the centre of the cone and a reduced density of sightlines in the periphery of the cone, in line with the phenomenon of focal sharpness/blurriness in visual space perception (see Figure 1). Any geometry of visual cone can be achieved by means of the parametric adjustment of the shape filter just mentioned. Each sightline delivers an individual data-sample when intersecting surrounding geometry. These samples are continuously processed by means of weight filters. The weight filters are defined in accordance with the definition of the spatial quality to be measured. In particular the relation of distances x obtained by perception rays with respect to the quality to be measured expressed in the functions of the weight filters. In visual openness measurement, preliminary a sigmoid-based function is used as weight filter.

$$S = \frac{1}{1 + e^{-\left(x - \frac{l_{\max} - l_{\min}}{2}\right)}} \tag{2}$$

In visual privacy and spatial intimacy measurement, preliminarily Butterworth function is used.

$$S = \frac{1}{1 + \left(\frac{x}{l}\right)^{m}} \tag{3}$$

The function parameters can be modified to adjust the measurement calibration to match with different definitions measurement conditions. Alternatively to Sigmoid and Butterworth function, weight-filters based on fuzzy membership functions can be used. Thereby the weight-filtering can be controlled in a more detailed way, to match any non-linearity of distance-based perceptual quality definition. In particular the phenomenon of distortion of the Mueller-Vieth horopter in visual perception, known as Hering-Hillebrand deviation (Howard and Rogers, 2002), can be taken into account in a fuzzy model. Details of the fuzzy modelling methodology are beyond the scope of this paper.

4. FROM PERCEPTION TO MEASUREMENT

4.1 Time series analyses

The weight-filtered samples are analyzed by means of a time-series analyses method borrowed from the domain of Signal Processing. This method is known as exponential averaging. Exponential averaging identifies average signal-values by means of continuous weight filtering of signal values using a time constant τ in this form.

$$\omega \equiv 1 - \frac{1}{\tau} \tag{4}$$

The time constant represents the size of a time-window in which samples are averaged. The time window moves forward in time, which corresponds to continuous update of the average value, which is incorporation of one new sample and dropping the latest sample at each time-step. At each time step q the new exponential average P_q of the signal S_q is computed in this form.

$$P_q = \omega P_{q-1} + (1-\omega) S_q \tag{5}$$

Contrasting conventional averaging methods, in exponential averaging previously obtained average information is incorporated in computation of the current average. This way the average, which is the measurement outcome, is updated in real-time in a computationally efficient and effective way (Ciftcioglu and Peeters, 1995).

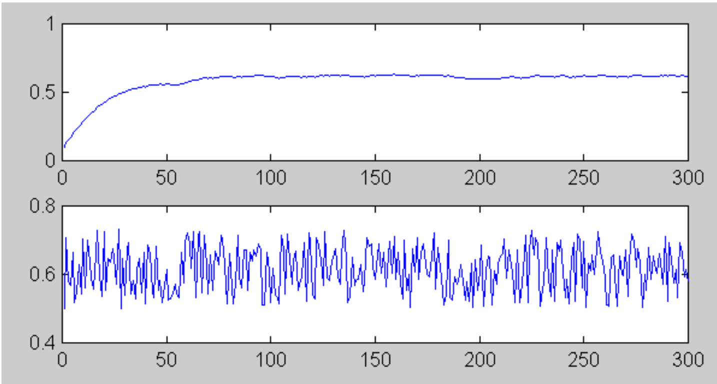

Figure 2. Example of a measurement. Below weight filtered perception samples S. Above exponential average P.

After some time, with no changes to the measurement system, the measurement stabilizes at a certain value (see Figure 2). Proportional to the time constant this stabilization is more or less quickly establishing, and is more or less stabile. In situations of static measurement conditions, a greater time constant yields a more accurate measurement. Latency effects of exponential averaging in transition conditions apparently correspond to the phenomenon of spatial memory in visual space perception. Transition conditions are changes in the measurement system over time, in our case in the form of translation and/or rotation of the cyclopean eye of the measurement system or modifications of the geometry surrounding the eye. Establishment of new average values in such transition conditions take time, which is termed measurement latency in this context. This latency is proportional to the time constant provided constant processing frame rate. The following example serves to illustrate the significance of this inherent property of exponential averaging in relation to visual space perception, in particular to the phenomenon of spatial memory in transition conditions. A person looking around or moving through an environment generally receives different openness impressions at each instance. However the previous impressions are not forgotten immediately but remain in the consciousness of the perceiver (Baddley, Logie..). This effect appears to correspond to the latency effect of exponential averaging method presented earlier. Greater values for τ correspond to greater spatial memory.

4.2 The Concept of Memory Time in Perception

In attempts of modelling real-time visual space perception, which is matching of time durations for establishment of computational perception assessments and human perception, another property of real-time systems has to be considered, which is expressed in the concept of constant memory-time. According to this concept, which is borrowed from the domain of real-time systems engineering, multiplication of time-constant τ and the reciprocal value of the computational frame-rate are a constant number termed memory-time μ .

$$\mu = \tau \times \frac{1}{f} \qquad (6)$$

Thereby, variation of computational frame-rate f is reflected in the measurement in the form of variation of the time constant. Slower computational processes, which are processes with a lower computational frame-rate, imply smaller time-constants and vice-versa. Experimental verification of the system variables can be conducted, which is beyond the scope of this paper. The parameters of the Gaussian shape filter, the weight-filter functions and the time-constant of the exponential averaging can be modified in real-time. Thereby the measurement system can be calibrated based on differently shaped visual perception, particular definitions of visual openness, visual privacy, and spatial intimacy, and individual difference in spatial memory and computational frame-rate.

4.3 Measuring Geometric Variance

Perceptual geometric complexity measurement, contrasting the measurements of the other perceptual qualities, is defined in this context as the exponential average of the variance of the distance samples. The complexity measurement is done by variance computation of the perception signal P in this form.

$$C_q = \omega \times C_{q-1} + (1-w) \times x^2 - P_q{}^2 \qquad (6)$$

The greater the variance of the perception samples, the greater the perceived geometric variance. As consequence of this definition, the geometry perceived as most simple is the interior of a sphere perceived from its centre position. An example of a space with a high perceived geometric variance is the centre of a tree top, where distances to individual opaque points strongly vary.

5. EXPERIMENT

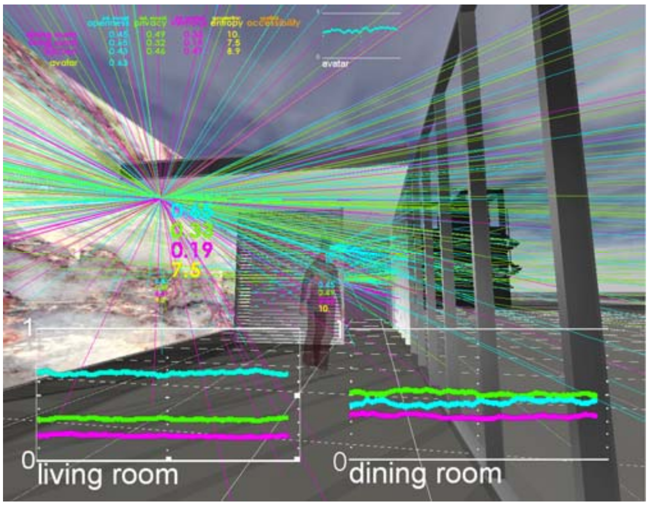

Figure 3. Real-time measurement of perceptual qualities in a design

In the following, a number of measurements are presented which were taken from several positions in a design. The design contained a number of geometric details, such as facade studs, screens made from horizontal louvers, windows doors, etc. Above Position 1 no ceiling is designed yet, above all other positions there is a ceiling located at 2,65m height.

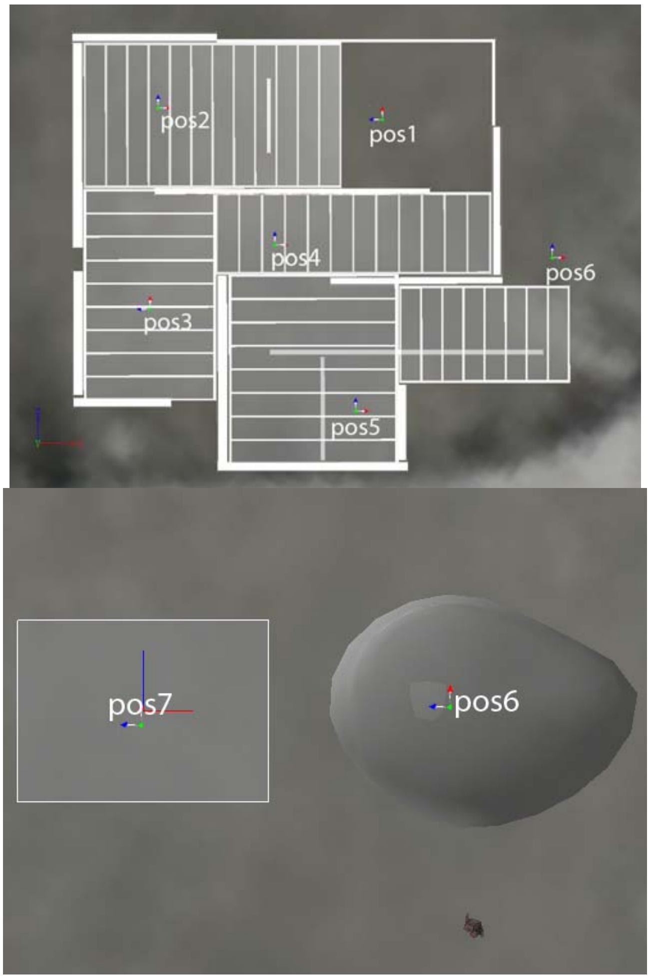

Figure 4. Plan view of measurement positions

The locations of the measurement positions were as shown in figure 4. Height of the measurement positions was chosen to be 1,70 above floor height, which is around average eye height. The parameter settings for the measurement system were as follows.

Table1. Parameter settings of measurement system for experiments

	visual openness	**visual privacy**	**spatial intimacy**	**geometric variance**
Shape filter				
(x_{mean}, x_{dev})	(0.00, 1.00)	(0.00, 1.00)	(0.00, 1.00)	(0.00, 1.00)
(y_{mean}, y_{dev})	(0.00, 0.02)	(0.00, 0.01)	(0.00, 0.50)	(0.00, 0.01)
(z_{mean}, z_{dev})	(0.00, 1.00)	(0.00, 1.00)	(0.00, 1.00)	(0.00, 1.00)
Weight filter				
function	sigmoid	Butterworth	Butterworth	Butterworth
lmax	4.5	7.5	4.0	7.5
lmin	1.8	3.0	1.8	3.0
m	-	2.0	3.0	2.0
Exp. averaging				
time constant τ	400	400	400	200

The shape filter was set to simulate 360 degree perception in the horizontal plane with some divergence in vertical direction off that plane (see y_{mean} , y_{dev} in Table 1). The setting of the weight filter parameters is suitable for interior measurements, based on previous tentative experiments. The time constant setting for the experiments is τ =400 and τ =200. The exact setting of the time constant is irrelevant in this experiment since transition conditions were not involved, real-time perception was not considered and the measurement was obtained after stabilization of the measurement outcome. With a high value for the time constant, after sufficient measurement time, the measurement stabilizes at a certain number. This number is the measured value of the perceptual quality.

6. RESULTS

The measurement outcomes for the measurements based on the system settings given in Table 1 and the positions indicated in figure 2 are as follows.

Table 2. Measurement outcomes

	visual openness	**visual privacy**	**spatial intimacy**	**geometric variance**
Position 1	0.72	0.34	0.19	6.6
Position 2	0.50	0.48	0.33	7.6
Position 3	0.48	0.50	0.29	10
Position 4	0,52	0,49	0,36	12
Position 5	0,17	0,80	0,61	1,6
Position 6	0,73	0,33	0,21	5,3
Position 7	0,30	0,65	0,48	4,6
Position 8	0,30	0,65	0,52	4,8

The outcomes presented in Table 2 are normalized since the weight filtering delivers normalized output (see formulae 2 and 3). Based on preliminary experiments the measured values appear to be in accordance with expectations based on visual inspection of the design, both in plan and from 1st person perspective. Small deviation in personal judgment may be due to imprecision in judgment. Larger and in particular structural difference in personal judgment and measured values may originate from various source. An individual may have a particular shape of visual perception or a particular definition of the weight-filtering parameters. Experimental identification of such difference can be conducted and thereafter knowledge-based calibration of the measurement system is possible by means of evolutionary search algorithms, which are a methodology from the domain of Computational Intelligence. This methodology can systematically find those settings of measurement system parameters, which yield minimal deviation to experimental data obtained by statements of test persons. Details of this procedure and methodology are beyond the scope of this paper. Measurement latency of exponential averaging, mentioned earlier, can be reduced by incorporation of Kalman filtering for smoothing in the measurement system, which is a sophisticated modelling methodology from the domain of Signal Processing. Via Kalman filtering the establishment of average signal values is obtained faster than via exponential averaging alone. Kalman filtering essentially models and eliminates process noise. Details of the method are beyond the scope of this paper. A particularly interesting result is the geometric variance assessment of position 7 and 8. Here the interior of a blob and a box geometry are measured. Although blobs are often considered to have a complex geometry with string variance in curvature, this perception based measurement reveals that in fact the blob geometry has a rather low geometric variance, very similar to the measured variance of a box. From a perception viewpoint both geometries differ only slightly in their geometric variance. This is not surprising considering that blobs are generally geometries with strong affinity to the sphere, which is the geometry with least variance according to our definition. Detailed analyses of the variance measurement by means of wavelet analyses, which is an advanced signal analyses methodology from the domain of Signal Processing, indicate that there is notable difference in the characteristics of the individual composition of blob and box geometry concerning their variance signals. This is due to difference in smoothness/edginess in both geometries.

The outcomes of the measurements are plotted in graph form in real-time. This way the designer has real-time feedback concerning the implications of his design actions with respect to the perceptual qualities, which are measured. The outcomes are used to assess requirement satisfaction in real-time. A number of demands are expressed in the form of required values for individual qualities and respective tolerances. The tolerances are translated to weight-factors by means of simple fuzzy membership functions. Individual deviation from demands is thereby weighted according to relative importance among requirements. Satisfaction of the overall design requirement is assessed in real-time. This outcome can serve as fitness assessment in computational design optimization.

7. CONCLUSIONS

The real-time measurement system presented in this paper is able to measure perceptual qualities in real-time, based on the definitions given. The measurement system can be calibrated in real-time to match individually different visual perception as well as individual definitions of perceptual qualities. The system deals with any detail level of geometric detail in the design. It provides measurements in real-time and handles transition conditions. Therefore it is particularly suitable in design, where fast response to design modifications is rather imperative for optimality search. Methodologies from the domain of Signal Processing, in particular exponential averaging, are suitable for computational perception modelling in particular perception based design assessment. The setting of the time-constant in exponential averaging can be adjusted in real-time to model time-based visual space perception, which introduces the concept of memory-time from systems engineering to architecture. The measurement outcomes form essential contribution in holistic requirement satisfaction assessment by resolving a traditional bottleneck in computational design, which is to deal with perception related design qualities. Such assessment is imperative basis for systematic optimality search, which is the essential process in design.

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