Computational Architectural Neuroscience: Towards the Computational Theory of the Human Brain Interactions with Architectural Design

H. Mirkia1, A. Sangari2, M. Nelson1, M Sarmadi1 and A. Assadi3
1Design Studies Department, University of Wisconsin, Madison, WI, USA
2Electrical and Computer Engineering Department, University of Wisconsin, Madison, WI, USA
3Mathematics Department, University of Wisconsin, Madison, WI, USA

Abstract - This article illustrates the opportunities and the challenges in an emerging multidisciplinary research area in study of human brain interactions with architectural design: Computational Architectural Neuroscience. We propose to apply main-stream methods from computational neuroscience to transform the commonly static formulation of the interior design evaluation problem into a dynamical systems formulation, which is the hallmark of modeling brain response and human behavior. While navigating indoors, observers experience perceptual features that often represent a synthesis of their visual perception of natural scenes, which are shaped and guided by the design and creativity of the architects. We propose to analyze the dynamic patterns of brain-generated signals in relation to perception of harmony of a design and decision making by human observers. We argue the feasibility of the methodology and efficiency of proposed algorithms to provide a quantitative theory of interior design evaluation in the cases considered below.

Keywords: Interior design, Computational neuroscience, Optical flow, Visual perception

1 Introduction

A challenging problem of theoretical and practical significant in design studies is whether it is possible to develop quantiative measures for evaluating alternative design solutions on a single project. Is it possible to develop quantitative measures for objective classification of separate design projects that might be considered comparable? Aesthetics and human response to aesthetics in architecture are sometimes described in relation to mathematics and geometry. However, the strength of this relationship is difficult to test empirically. If evidence could be shown that this relationship holds true, then computational methods using mathematics to analyze spatial geometry could be used to predict the human response to aesthetics as they exist in a wide range of design solutions. Furthermore architecture, especially interior space, is perceived dynamically during one’s movement through space. At the same time study has shown that visual perception is shaped by eye movement that creates a dynamic series of spatial vignettes. While this dynamic series might seem to be difficult to express as a two dimensional static construct, artists have successfully tackled similar problems. This paper proposes a computational model that would predict human response and aesthetics through empirical analysis of the geometry of dynamic two dimensional images of a design that are linked with neuroimaging of the brain occurring while looking at those images.

The content of this article are as follows. We outline the basic background from computational neuroscience to investigate how the brain is likely to respond to harmony of design in interior spaces. The first observation, which we introduce as a way to study a design is the role of “perceptual dynamics” in the human-centric evaluation and appreciation of design elements. This is accomplished by elucidating the manner that eye movement provides the sensory input in to the observer’s visual cortex. Eventually, such information is transmitted to higher cognitive areas, and interacts with the affective centers of the brains such as the amygdala. This can be measured by using eye tracking equipment, thus, the availability of a rich source of empirical data from highly relevant brain activities. The second observation concerns a theory for visual perception of perspective in interior spaces. The brain area used to interpret perspective can be measured by using neurological imaging. Accordingly, the area of the brain (MSTd) that is known to contain the neurons and local circuits for perception of optical flow appears to be the site of local circuits that make the most significant contributions to detect perspective in interior spaces. By bringing these two observations together in a computational model, we simulate a simplified version of the brain processes for perception of interior space as a dynamic event. Thus, we demonstrate the mathematical feasibility for a quantitative theory of design in which some of the fundamental design principles found in high quality human centric design could be subject to systematic measurement in the context of whole designs. Further, we discuss an approach for practical implementation of algorithms to quantify certain aspects of harmony and facility in communication of design elements.
2 The Central Theme: Quantifying Design

The contemporary architect implicitly considers the psychological factors in design of interior spaces to invoke the sense of harmony and positive affect in the observers. We outline a unified framework for quantifying the perception of geometry and motion in interior spaces, situated in the psychological foundation of integrative affect and cognition, as a way to evaluate anthropocentric interior design. A systematic mathematical-behavioral framework to model design of interior spaces is Perceptual Geometry [2, 4]. This interdisciplinary research area focuses on study of geometry from the perspective of visual perception, and in turn it applies such geometric findings to the ecological study of vision. The aesthetic aspects of interior design beyond geometry require a deeper study into the affective dimensions of psychology than what is touched upon below. Perceptual geometry is used to investigate quantitative and cognitive aspects of a design with the goal of attempting to answer fundamental questions about the synthesis of perception of form and representation of space. This is paired with biological theories of visual perception and geometric theories of the physical world. The contribution of this paper is to start with the view that perception of form, space and motion are facets of the same computational steps in the observer’s brain, and then to argue a hypothesis that mathematical modeling and machine learning can replicate many of the same computational steps as the brain. Our approach incorporates mathematical translation of the following indicators of harmony in interior design: (1) The observer’s attention is guided through a configuration of lines; (2) the design elements are communicated easily to the observer to facilitate remembering the information. We propose adding a third indicator, which should be quantified in our model using brain imaging and psychophysics; namely, (3) a significant part of the affective response of the observer arises from the observer’s attention to salient features of the design.

3 Methods and Discussion

In this section, we sketch the steps for development of a mathematical model for “quantifying design,” that is, to assign numerical measures that evaluate the above-mentioned three principles indicators of harmony in design. This hybrid of empirical mathematics, computational neuroscience and perceptual psychology proceeds to quantify design in several steps, as outlined in Figure 2 below. To begin with, we need to validate the assertion that the line-drawing abstraction of a design project faithfully conveys the simplest visual-cognitive representation of that project. This step uses experiments with tracking of observer’s eye movements and analysis of such data. The (dynamic) data sets are collected in two parallel cases of visual perception: First, perception of the line-drawing as a candidate for simplified medium for communication of design in the project without loss of perceptually critical information; second, eye movement tracking in visual perception of the original design project. The output of this step is selection of a collection of “optimally simplified line drawings” of the project that we refer to as the “design perceptual minimal models.” The implementation of this step requires a sufficiently large database of design projects, which are processed by algorithms for extraction of line drawings. These line-drawings must be incrementally “simplified” without loss of critical information about the design, through repetitive psychophysics experiments that uses evaluation of eye movement records as the fundamental tool for comparing two line drawings, and deciding which is “simpler without loss of information,” or, having reached the choice between a minimal model and the line-drawing that is over-simplified by removal of a single line from the minimal model. The mathematical result of these operations is an algorithm for “model reduction,” which provides the basic elements for the Empirical-Mathematical Theory for Quantifying Design. Due to space limitation, we omit the discussion for an efficient strategy of using functional brain imaging (or an equivalent method) to test and validate the outcomes of the mathematical model/theory.

The workflow of our model (Figure 1 below) yields outputs that are observer-dependent. Moreover, there could be several “simplest models at the psychophysical threshold,” thus several minimal models for the same design project. The design expert then selects one or two minimal models as the “best representatives of design elements.”

Figure 1: The workflow of the model for quantifying design.

We measure the brain activation level of the observer by fMRI (or other noninvasive brain imaging). We associate a cost function from the fMRI experiment to the line-drawing that is “perceptually minimal.” The lowest value of the cost functions is the quantitative cognitive/perceptual measure for the design. There is a minimal exposure time (threshold time) that the observer’s brain needs to process the sensory stimuli and for the perceptual subtasks to take place, in order to reliably distinguish the design element in the project; and a lesser exposure time could confound the observer with a large statistical error. We hypothesize that the observer’s brain must extract a minimum level of information in order to achieve this. The perceptual state of the brain, we hypothesize to have constructed an entity, which we refer to as design perceptual minimal model. The dynamic processes for
extracting the information for design perceptual minimal model are commensurable to the dynamic processes that the brain generates to reconstruct the Gestalt of design elements (Just Noticeable Difference in psychophysics).

We also propose the existence of neuroanatomical loci that play a pivotal role in perception of perspective, and demonstrate a mechanism for visual perception of interior spaces based on eye movement. We conclude that learning to estimate motion from optical flow is similar to learning to estimate a single vanishing point. [1]

The study of 3D perception from 2D images is the main issue of vision science in both biological and computer systems. Depending on the projection method used for mapping 3D space to a 2D plane, different images may be resulted. Among these projection methods, perspective projection is known as an accurate mapping for reconstructing geometrical features of real objects. One important concept in perspective projection is the “vanishing point”. The vanishing point of a straight line under perspective projection is that point in the image beyond which the projection of the straight line cannot extend. Therefore, the vanishing points correspond to the “points at infinity” in the receding direction of the parallel straight lines in space.

Computationally, the vanishing point in interior spaces with a single vanishing point can be found by finding the point where most of the salient straight lines in the image intersect with each other. The salient straight lines can be found using processes such as edge detection and line extraction. The mechanism of edge detection in the brain is related to the lateral inhibition in the receptive field of the visual sensory system [8]. A sample of how edge detection occurs in an interior space is shown in Figure 3, center.

The Gestalt principle of continuity shows how the brain can fill in the gaps between the dots in the image and extract the major lines. The Hough transform can be used to extract the slope and the constant term of lines in the image, based on black and white result of edge detection algorithms [3]. The line drawings made from the interior spaces of Figure 2, center carry pieces of information that the brain needs to estimate the orientation of surfaces and compute the perception of the interior space in perspective. By extending these lines and finding the intersection points, we can computationally find the vanishing point (Figure 2, right).

In real word experience, additional information such as texture, color and cues provide much more useful information for richer perceptual experience of interior spaces [2], [4]. However, this method focuses on simpler geometric objects as illustrated in the line drawings below.

**Figure 2:** Two steps in detection of vanishing point: edge detection of local circuits in area V1 and the thalamic feedback system provide the information about the lines as above. We have simulated the extraction of lines using Hough transform. (a) Left: an image from the Wisconsin Institute for Discovery (WID). (b) Center: binary output of edge detection. (c) Right: overlay of the Hough transform output onto the original image.

### 4 Algorithms and Computations

The conventional static view in decision making regarding interior design alternatives focuses on the interactions among design elements and the established principles for harmony and aesthetics. To transform this static formulation into a dynamic framework, we consider the human brain response to navigation indoors while interacting visually with design elements and eventually arriving at decision making among alternatives. A key step in computational neuroscience modeling of observer’s decision making is to elucidate the neuronal mechanisms that incorporate the observer’s prior experience of perception of navigation indoors in order to form top-down flow of information (in the Bayesian sense). Optical flow is a primary computational theory for observer’s perceptual mechanism governing navigation. Our computational model for an observer demonstrates that prior experience from optical flow considerably improves the observer’s performance in identifying perspective geometry, compared to the performance of the "naive observer model" that must learn the geometry of lines *ab initio*. We would expect that the measurement of the observer’s brain activity when presented an interior design project, and the record of the eye movements (see the work flow) would be an unbiased representation of the correlations among perception of perspectivity (the primary factor in interior space design) and navigation indoors. Therefore, comprehensive data collection as discussed above is very likely to lead the anticipated results for quantification of dynamic patterns of brain activity in response to interactions of the observer and design elements. Finally, we invoke the hypothesis that the facility in reaching the Gestalt of a design project (shortest time to form stable perception, while performing better or within the designated error rate) indicates the observer’s decision regarding which design alternative could be the most harmonious. Below, we outline the computational model for identifying perspective geometry in the context of optical flow, which simulates experiments in quantifying performance of observer’s perception of interior space.
We have developed a unified framework for perception of geometry and motion in indoor environments. We designed some 3 dimension interior spaces and import them in a virtual reality environment. We use the principal component analysis for reducing dimension of successive frames of this simulation and take some of the most informative components in training a neural network (Optiflonet) for estimation of direction of movement in the image plane. Then, we show this neural network with slightly different configuration can extract the vanishing point in still images.

In our model, we have simulated the sensory information by architectural rendering of the some simple designs (such as Fig. 3). In order to test motions with more complex kinetics, we used virtual reality techniques in rendering these simple interior spaces. We compare extraction of lines from simulated scenes versus extraction of lines in natural scenes.

![Figure 3](image1.png)

**Figure 3:** This is an example for training validating and testing a neural network that learns to extract the vanishing point as a significant piece of geometric information for extraction of orientation of surfaces from directions of lines (edges) in the sense.

We now discuss learning perception of self-motion characteristics from optical flow. When an observer moves in an interior space, optical flow provides a robust mechanism to estimate the motion and heading direction. The optical flow vectors indicate the distribution of stimulated local circuits that detect motion heading direction. Optical flow vectors, (the arrows in the figure 4) can provide the input for training our neural network Optiflonet. Validation and testing of neural network are performed using 600*300 arrays with sparse sampling of the optical flow vectors. As it is illustrated in figure 4, for simple interior spaces, optical flow vectors can be approximated by a spars matrix. Therefore, we use principal component analysis for extracting the most informative components of optical flow vectors in all frames.

![Figure 4](image2.png)

**Figure 4:** Optical flow vectors in simulated interior space movement. Right image shows the area inside rectangle with magnification in order to emphasize the small optical flow vectors.

We use the first 60 principal components of image frames in order to reduce the required number neurons in our neural network and in the meanwhile avoid the reconstruction errors. Figure 5 shows the whole structure of Optiflonet system for estimation of motion direction in the image plane, also the architecture of neural network that we used is presented in figure 6.

![Figure 5](image3.png)

**Figure 5:** Flowchart of data processing in Optiflonet from image frames to estimation of motion direction in image plane.

![Figure 6](image4.png)

**Figure 6:** This figure shows the architecture of Optiflonet neural network. It has two layers of neurons and in the hidden layer there exits 100 neurons.

To test our theory we designed a neural network that learns to extract vanishing points from perspectives called Perspectinet. This network incorporates a simplified model of eye movement, which passes sampling of the scene as a flow of consecutive snapshot of the interior spaces from an eye with movement. Consequently the subsequent layer of Perspectinet receives dynamic information from the scene. Design of Optiflonet is based on the figure 7. The optical flow from movement on the retina provides the input to the next layers of visual sensation and visual perception of motion.

We propose a model that an observer brain estimates perspective from prior experience of navigation in indoor space in the context of optical flow. We train an Optiflonet using examples of navigation in an interior space. The model uses training sets that are temporal sequences of image samples, where each image frame is a snapshot of the interior space in perspectives projection. The observer’s movement indoors provides different projections on the retina; consequently, different perspectives are registered with possible shifts in the vanishing point. The perspective could be tested in the following way: The dynamic scene (perspective images) turn into a movie that represents the effect of eye movement. Subsequent blocks have layers of the network and connection-weights that are inherited from training the Optiflonet. Our problem is to introduce and measure the performance of the Perspectinet when test images are from interior space without any training by feedback from this category of interior space forms. In other words, the local circuits of Perspectinet in the visual motion processing layers are used as local neural circuits that are
employed for computations in image sequences of eye movement snapshots from interior spaces forms.

**Figure 7:** Flowchart of data processing in *Perspectinet* from the still image to extraction of vanishing point in the image.

### 5 Results

In order to train *Optiflonet* we used back propagation method on our training data set. Training data set contained the 150 frames from a simulation of walking through a corridor like that in figure 3. We used another set of 150 frames for validating and testing of our neural network.

Also, figure 8 shows the error in estimation of motion heading in horizontal and vertical axis of each frame separately. Since in training and test data we use a simulated walking, the kinetic of movement (velocity and orientation of camera) through interior space was stochastic variable.

**Figure 8:** Histogram of output error during the testing *Optiflonet* neural network. Left: error in estimation of movement heading (in degree) along vertical axis of frame. Right: error in estimation of movement heading (in degree) along horizontal axis of frame.

In figure 9, we presented the time series of camera velocity and orientation during recording frame data for training. The orientation of the camera is shown by 3 component of the unit vector parallel to camera orientation.

**Figure 9:** Time series of camera velocity (right plots) and orientation (left plots) during the recording data for neural network training.

Finally, the histogram of error in detection of vanishing point location in different frames is illustrated in the two histograms of figure 10. The left histogram shows the vertical error while the right one shows the error along horizontal axis of frame. The maximum error in horizontal axis is generally less than 1 degree and in the vertical axis is always less than 10 degree.

**Figure 10:** Histograms of output error during the testing of *Perspectinet* neural network. Left: error (in degree) in estimation of horizontal component of vanishing point along in the image. Right: error (in degree) in estimation of vertical component of vanishing point along in the image.

### 6 Conclusion

While the analytically based methodology described here has additional nuances and detailed applications beyond the scope of this preliminary paper, we believe that this methodology can be applied to a large sample of images of interior architectural space in order to identify potential standards for quantifying design elements, the central problem of design studies. Furthermore, meaningful computational analysis can be applied as a way to predict the human emotional response to design of interior space.

While the central problem of quantifying design remains to be studied in more detail, we believe this article’s computational methodology provides optimism for rapid progress in near future to overcome the theoretical and experimental challenges that Computational Architectural Neuroscience must overcome. In particular, we predict this emerging multi-disciplinary research direction will formulate and develop the computational framework to quantify significance of high quality principled design in human health and well-being.

### 7 References


