Space Perception in Real and Pictorial Spaces: Investigation of Size-Related and Tone-Related Pictorial Depth Cues through Computer Simulations

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ABSTRACT

Extensive studies on the depth perception of real space have enriched the knowledge of depth cues and have advanced the realism of the creation of pictorial space. Architects often use pictorial space mediated on two-dimensional media to envision design alternatives and their resultant three-dimensional qualities of un-built spaces. Thus, the knowledge of pictorial depth cues can be employed in design considerations to enhance the spatial experience of built environments. Recent developments in computer graphics of physically based renderings and perceptually based tone-mapping techniques are utilized in this paper to generate pictorial spaces that can reflect perceptual reality. Psychophysical experiments are conducted to investigate the size-related and tone-related pictorial depth cues in this alternative environment. There are two objectives of this study: the first is to ensure that the size-distance relationship, the underlying principle for size-related pictorial depth cues, can be observed effectively in a computer-generated pictorial space; the second is to demonstrate that perceptually based computer simulation can be utilized to conduct perceptual study on tone-related pictorial cues that are otherwise restricted from the physical setting and, in turn, to provide a pictorial environment for envisioning the effect of the studied pictorial depth cue in the design process.

Keywords: space perception, depth cue, physically based rendering, tone mapping.
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1 INTRODUCTION

The three-dimensional (3D) visual environment of an existing space is understood through the visual processing of two-dimensional (2D) retinal images [21]. On the other hand, 2D representation systems are utilized to develop 3D un-built proposals, and to provide instructions for constructing the projects [4]. Depth cues are the contextual information available from a scene that can be used to recover the third dimension of depth that is lost in the process of optical projection from a 3D scene to 2D retinal images [14]. They can also be used to create the illusion of pictorial space on representational media [4].

Any representation is an abstraction and simplification of the subject being represented, and is developed to offer various degrees of realism to the function it is called to serve [34]. The function of the representation sought in this study is to provide an alternative environment, other than the physical environment, to study the effect of depth cues and, in turn, to provide a pictorial space for envisioning the effect of a studied depth cue in design applications. In order to employ the studied depth cue as a design parameter, this research describes a particular approach that utilizes a 2D pictorial environment to conduct psychophysical experiments that establish the quantitative relationship of depth cues and their impact on the perceived distance of a 3D space.

1.1 Size-Related Pictorial Depth Cues

Visual perception is a complex process that involves the eye and the brain to interpret the 2D retinal images that are projected from the 3D world. At the retina, the energy of light is absorbed and converted to neural signals of luminance and color. The signals are then sent via the optic nerve to different visual areas in the brain for further processing [24]. Edges are detected from the luminance variations. From the enclosed edges, meaningful shapes and patterns are recognized. The brain searches for familiar 3D forms from memory and recalls the knowledge of depth cues to interpret the 3D forms and space [30].

The significance of detected edges in visual space perception can be observed when we attempt to create pictorial representations. Fig. 1 illustrates how the perceived luminance of a scene is processed into the perception of a 3D scene, and how the process is reversed to create the illusion of depth on planar media.

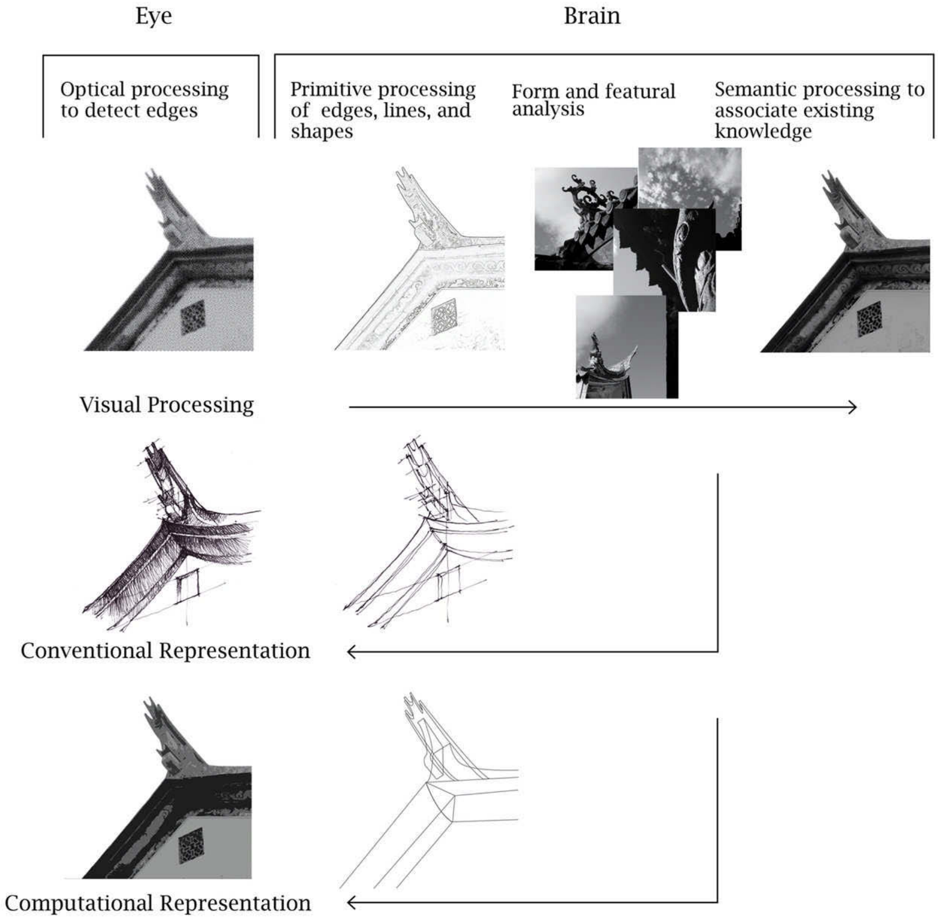


Fig. 1: Perception and representation.

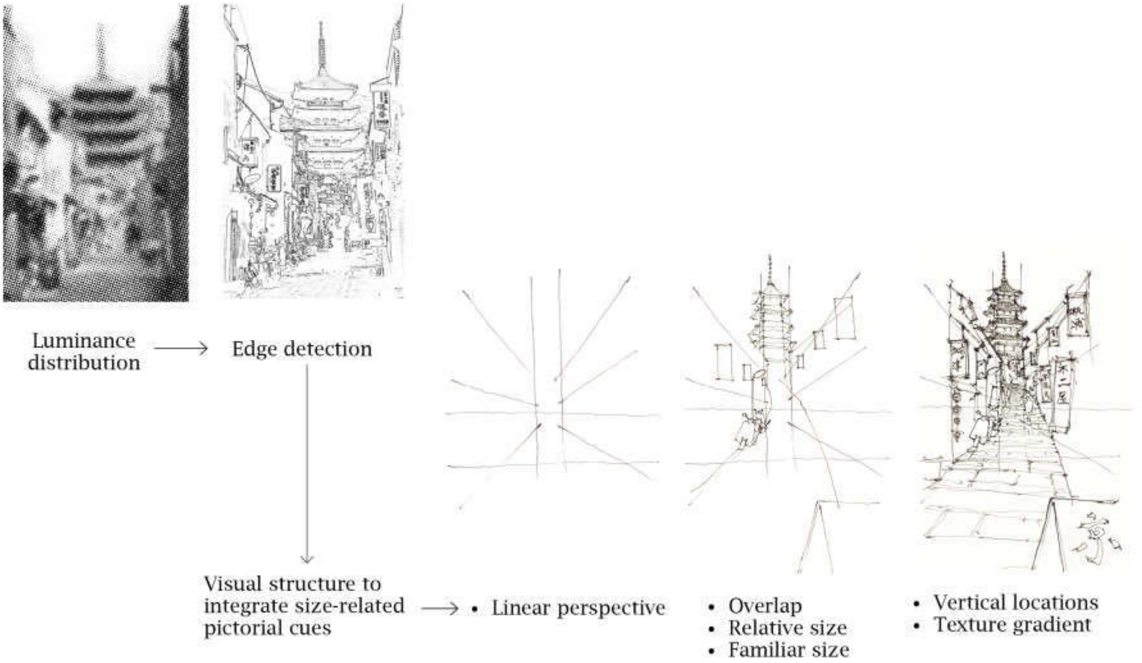


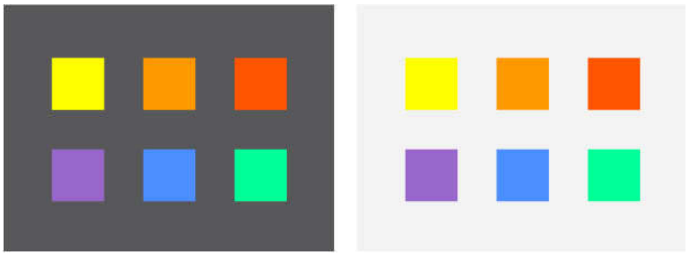
Fig. 2: Visual structure and integration of size-related pictorial cues.

The visual information provided by the detected edges facilitates the understanding of the geometric properties of the 3D scene from the 2D retinal images. The geometric properties are governed by the size-distance relationship, which states that the perceived size of an object is derived from its perceived distance [14]. This is the underlying principle for the size-related pictorial cues that include relative size, familiar size, linear perspective, and texture gradient. Because the detected edges are the processed visual information, reproducing size-related pictorial cues can thus be an abstract representation that does not require high levels of visual realism.

As illustrated in Fig. 2, the spatial structure that is abstracted from a perceived scene can be used as a visual guide for constructing the three-dimensional layout. By outlining the visual structure following the principle of linear perspective, it can integrate size-related pictorial cues to create a coherent representation of a 3D scene. As a result, size-related pictorial cues are not only dominant depth cues for perceiving the three-dimensional physical scene, but also effective strategies for creating predictable illusions of depth.

1.2 Tone-Related Pictorial Depth Cues

Tone-related cues, such as shading and atmospheric perspective, are inferred from the direct perception of the luminance distribution in a scene, and applied on the representational media as tonal values. By the use of the contrast of light and shadow, shading can be used to describe objects' 3D shapes, forms, and locations, but not to cue the overall spatial depth. Atmospheric perspective, also known as change of hue with distance, can only be observed in a natural scene from a great distance. For a shorter range of distance, Itten (1970) pointed out that the composition of different color variations can produce spatial effects on a planar surface (Fig.3) [16]. In a recent study of depth perception, Schwartz and Sperling (1983) formalized perceived luminance as a pictorial depth cue [29]. O'Shea, Blackburn, and Ono (1993) further conducted a perceptual study, and suggested that it is the contrast of luminance that cues the distance (Fig.4) [20]. However, those studies are limited to a planar display, and fall short of addressing the spatial and luminous complexities of a built environment.



(a) (b)

Fig. 3: Demonstration of the spatial effect produced by the composition of different color variations: (a) yellow patch appears to advance with dark background, (b) violet patch appears to advance with light background.

(a) (b)

Fig. 4: Demonstration of the spatial effect produced by contrast: (a) light square appears closer with dark background, (b) dark square appears closer with light background.

1.3 Perceptual Studies on Depth Cue

Studies on space perception often ask subjects to view a target (standard stimulus) in a test scene, and then to adjust a target (comparison stimulus) in a reference scene to match the perceived distance of the test target. The difference between the measured perceived distance of the reference target and the actual distance of the test target could reveal the quantitative effect of the manipulated depth cue between the test and reference scenes. Various size-related pictorial cues have been studied through this research framework. However, studies on tone-related pictorial cues are often restricted because of the many limitations in controlling the complexities of the luminous environments of an architectural scene.

The perceivable luminance range of a real scene can be wide. In fact, it is so wide that the human visual system has developed a complex adaptation mechanism that is sensitive to a range of 4 logarithmic units at a given moment, and up to 14 logarithmic units overall. This dynamic perceivable range and the complex visual adaptation process have limited the feasibility of perceptual studies on the quantitative impact of scene-based luminance distributions on depth perception. As a result, while the knowledge of size-related depth cues (facilitated by the edges detected from the luminance variations) is well understood, little is known about the direct contribution of luminance distribution patterns (tone-related depth cues) to our perception of depth.

The pursuit of realism has been one of the research goals in computer graphics. Realistic image synthesis focuses on the simulation of the luminance environment as observed in physical scenes. The resulting 2D image provides scientific accuracy of the luminance distribution, in addition to artistic visual appeal [22]. The first task undertaken in this study was to draw from the latest developments in computer graphics, and to develop a computational framework to generate a pictorial space that can reflect perceptual reality. The goal is to equate the depth perception of real and pictorial spaces, and to develop a methodological framework to investigate the depth effect of the tone-related pictorial cues contributed from the luminance distribution in architectural scenes.

2 PERCEPTUALLY BASED COMPUTER SIMULATIONS

Computer rendering is defined as the process of making a 2D image from a 3D scene. It is a pipeline process that involves constructing 3D geometry, defining the properties for surface materials and light sources, composing a 2D view, computing the interaction of the light transport within the scene, and rasterizing a 2D image [33]. Different rendering algorithms have been developed to offer various degrees of visual realism for the final output.

2.1 Physically Based Renderings

Physically based rendering aims to generate images that can mimic physical processes in the real world. In the physical world, vision involves the interaction of the visual system, light emitted from sources, and light reflected within the environment. In physically based rendering, geometry, material, and lighting properties are defined based on their physical properties and algorithms that represent their physically based behaviors.

The RADIANCE Lighting Simulation and Rendering System [31] is a physically based rendering tool. It uses Monte Carlo backwards ray-tracing algorithm to model light transport and output the resultant rendering in a high dynamic range (HDR) image format that encompasses numerically accurate luminance data [19].

2.2 Tone Mapping and Perceptually Realistic Pictorial Space

The HDR image can store the complete range of lighting data of a scene. However, the full range of luminance values contained in HDR images cannot be displayed on conventional display devices, which have a limited range of 2 logarithmic units [27]. Tone-mapping techniques have been developed to address this problem. They are used to compress the HDR data into a displayable range in a meaningful manner [32].

The visual system of humans consistently deals with dynamic range reduction. The dynamic range of the perceived luminance is reduced through visual processing from the retina to the brain. The underlying concept of perceptually based tone-mapping techniques is to create a compressed visual stimulus to be an equivalent stimulus in the later stages of visual processing, and therefore, to stimulate a similar visual perception of the depicted physical scene [27]. However, the complex process of visual perception has yet to be fully understood. Different tone-mapping operators have been developed based on different approaches with different approximations and simplifications.

Perceptual studies have been conducted to evaluate various tone-mapping operators. These studies can be grouped into three types, where different tone-mapped images are compared i) with each other [6], ii) with HDR images displayed on an HDR display device [18], and iii) with real scenes [3] [17] [36]. Although no single operator can be concluded from those studies that works for all types of scenes, the photographic tone-mapping operator has consistently provided good results. The photographic tone-mapping operator globally compresses the dynamic range, and then locally adjusts the pixel values to enhance the local contrast [25]. It reflects that the human's visual system adapts to the overall light levels and sees the environment based on that adaptation level, but also adapts locally as it scans the environment [27].

2.3 Framework for Physically and Perceptually Accurate Imagery

Physically based HDR images incorporated with tone-mapping techniques provide both numerical accuracy through physically based renderings, and perceptual reality through tone-mapping operators. The accuracy and appropriateness of utilizing RADIANCE renderings for psychophysical research studies have been demonstrated by Ruppertsberg and Bloj [28]. This computational framework has been used to simulate experimental scenes for investigating lightness perception [1] [9], color perception [2] [5] [35], and shape perception [10]. The experimental scenes used in this study adopt this framework; the images were generated by the RADIANCE rendering system and tone-mapped by the photographic tone-mapping operator to best reflect the perceptual reality of the physical scene.

3 EXPERIMENTAL INVESTIGATION ON SIZE-RELATED AND TONE-RELATED CUES

There are three variables in experimental design to establish the causal connections between a particular factor and influenced behavior: the independent variable, the dependable variable, and the extraneous variable [12] [13]. In an experiment designed to investigate the perceived luminance and its impact on depth perception, the dependent variable is the measurement of the perceived distance. The independent variable is the different distributions of lighting patterns for an architectural space. By comparing the differences of the measured depth perception for each condition, the cause-and-effect relationship of perceived lighting patterns and their impacts on depth perception can be quantitatively studied. The major challenge in physical environments is to keep the extraneous variables constant while varying the independent variables. A computer-generated pictorial space provides the flexibility to precisely control the extraneous variables from one experimental scene to another. However, the two-dimensional nature of the viewing environment restricts the method for measuring the perceived distance.

A verbal report is a straightforward method that simply asks observers to estimate the distance of the presented stimulus. However, this method is less objective, because it is dependent on the individuals' abilities to convert their perceived distances into predefined units, such as feet or meters. Phlibeck and Loomis (1997) established that blindfolded walking to a previewed target is indeed controlled by the perceived distance [23]. However, it is restricted to the availability of a physical site, because physical movements are required. In visual matching, observers are asked to view a target at a distance, and are prompted to set another target to match that perceived distance. This method is the most commonly used method that works well in physical environments. However, the full cue condition of a 3D scene is represented as a reduced cue condition on a 2D pictorial space, and the estimation of the third dimension of depth may not be as intuitive as it is in a physical environment.

Two-dimensional size has been promoted as an indirect visual matching method to measure the perceived distance [8] [11]. This method is built upon the size-distance invariance hypothesis that the perceived size of an object is derived from its perceived distance. By comparing the projected sizes of the same or different objects, our visual system can establish the relative distance between those objects in a 3D layout. Based on this relationship, the perceived size of objects in a visual field can cue the distance, and can thus be utilized as an indirect visual matching method in investigating depth perception.

In summary, the pictorial cue of the size perspective can be a dominant depth cue on a 2D representation of a 3D scene. In order to adopt a direct or indirect visual matching method to measure the depth perception in a computer-generated pictorial space, it is essential to ensure that the size-distance relationship can be observed effectively in computer-generated environments.

3.1 Classic Experiments of Holway and Boring on Size Perception

There are two hypotheses of size perception. The law of size constancy indicates that an object's perceived size is relatively constant, regardless of its distance. The law of visual angle, on the other hand, states that the size of an object should be determined by its projected size on the retina [21]. Holway and Boring (1941) conducted psychophysical experiments to examine these two hypotheses, and concluded that the perceived size of the object follows the law of visual angle in a perfectly isolated environment. However, with the presence of the contextual information of depth cues, size constancy takes place and allows the observer to recover the object's actual size [15]. The results confirm the size-distance relationship, and further indicate that the perceived size can cue the distance.

Fig. 5 illustrates the general setup for the classic experiment. An observer sat in a chair at the intersection of two long darkened corridors, where he/she can view the standard and comparison stimulus, respectively, from each corridor. The comparison stimulus (Sc) is a uniformly illuminated circular light-image projected on the center of an 8' by 8' white screen. It was fixed at 10' from the observer throughout the experiment. The standard stimulus (S) was provided in the same manner; however, its projected size on the screen and the distance from the observer was systematically varied. The screen was placed at various fixed distances, ranging from 10 to 120 ft. The size of S was enlarged as its distance to the observer was increased. At all distances, the circular light-image of S subtended a constant visual angle of 1 degree at the observer's retina. In each trial, the examiner regulated the size of the comparison stimulus until the observer signified that the standard and comparison stimuli were perceived to be equal in size. The observers were first fixated at the standard stimulus, then at the comparison, and they were allowed to look back and forth until a decision was made.

For each observer, the trials were repeated under four different conditions:

- In the “Binocular Observation” condition, the observer used both eyes.
- In the “Monocular Observation” condition, the observer used only one eye.
- In the “Monocular Observation with an Artificial Pupil” condition, the observer used one eye and observed the standard and comparison stimuli through a thin metal disk with a pupil (1.8 mm in diameter).
- In the “Monocular Observation with an Artificial Pupil and Reduction Tunnel” condition, a long black tube was installed to eliminate the perception of reflected light from the surfaces of the corridor, in order to further reduce the observation for the monocular observer with an artificial pupil.

Fig. 6 illustrates the experiment results. It was concluded that the more the reduction of the contextual information, the closer the result was to the prediction of the law of visual angle (as compared to the prediction of the law of size constancy). This classic experiment demonstrated that, with the presence of depth cues, human vision is able to maintain size constancy.

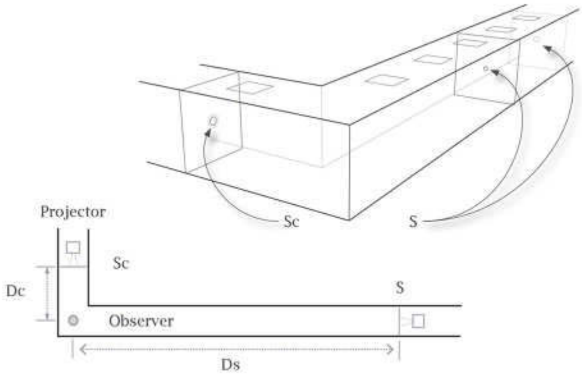


Fig. 5: Setup for the classic experiment on size perception conducted by Holway and Boring [15].

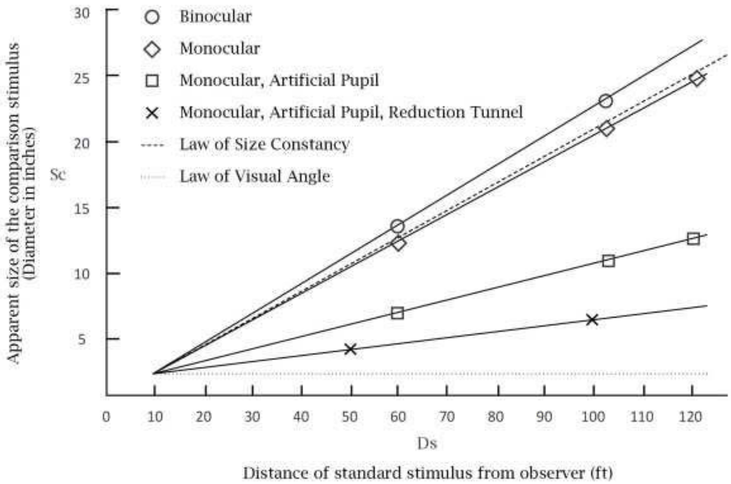


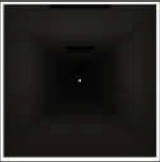
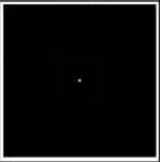
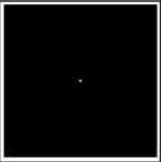
Fig. 6: Results of the classic experiment on size perception conducted by Holway and Boring [15].

3.2 Computer-Modified Experiments on Size Perception

The RADIANCE Lighting Simulation and Visualization System [33] is used for generating the experimental scenes in the computer environment. Linear tone mapping is used for digital images that have a displayable range. The photographic tone-mapping operator [25] is applied to scenes that have a wider dynamic range. The comparisons between the experimental results are used to investigate the credibility of using a computational framework to study depth perception through an indirect visual matching method.

In the classic experiment, the different conditions of standard stimuli can be considered as being controlled by the visibility of contextual information manipulated by the availability of light and the restriction of the view. In the modified experiment, because the standard stimulus is to be presented as a 2D image on an LCD monitor, where the full cue condition cannot be reproduced, the viewing of the standard stimulus is restricted to three binocular conditions. In each condition, the same set of computer-simulated scenes is presented with different contextual information controlled by the availability of the ambient light and the installation of the reduction tunnel. In order to reduce the duration of each trial, the number of different disk sizes is reduced from twelve to four. Each of the four scenes is composed by a disk with a radius of 1” located 10’ away, a disk with a radius of 3” located 30’ away, a disk with a radius of 5” located 50’ away, and a disk with a radius of 7” located 70’ away, respectively. Tab. 1 illustrates the simulated scenes with different configurations of disk size and location under three conditions:

- In the “Disk and Corridor Lighting” condition, the dim light from the ceiling and the luminous disk provide the full contextual information of the environment.
- In the “Disk Lighting Alone” condition, only the partial context surrounding the circular disk is made visible by the light emitted from the luminous disk.
- In the “Disk Lighting Alone with Reduction Tunnel” condition, the reduction tunnel is installed in the virtual scene, and it completely eliminates the reflected light from the corridor’s surfaces from the composed view.

Disk size (radius) and location	Conditions		
	Disk and corridor lighting	Disk lighting alone	Disk lighting alone with reduction tunnel
1" at 10'			
3" at 30'			
5" at 50'			
7" at 70'			

Tab. 1: Scenes of standard stimulus for the computer-modified experiment on size perception.

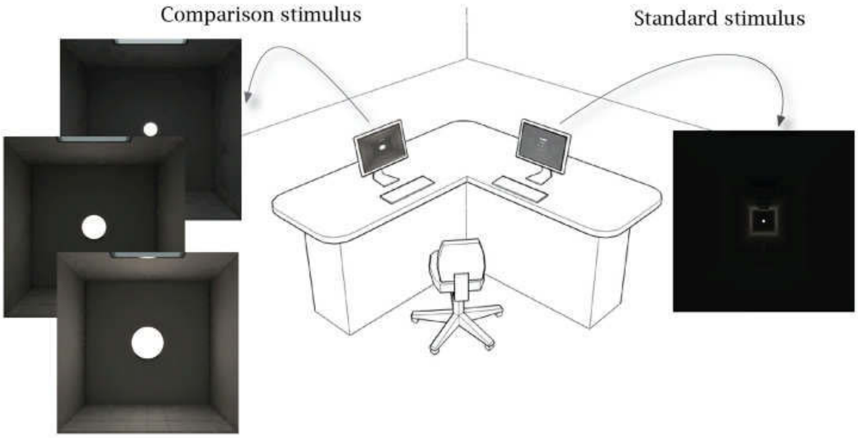


Fig. 7: Setup for the computer-modified experiment on size perception.

Fig. 7 illustrates the experiment setup. In each trial, the subject is presented with one of the images of the standard stimulus on one monitor. Each image is a rendering of a scene with unknown configurations of disk size, distance, and lighting condition. On the other monitor, the subject is instructed to adjust the disk size that is fixed at 10' by an on-screen control, to match the apparent size of the disk from the standard stimulus. Starting from the radius of 0.25", the subjects can increase or decrease 5 steps by a total of 1.25", and they can fine-tune their adjustments with one step of 0.25" at a time. The subjects first fixate at the standard stimulus, then at the comparison stimulus. They are allowed to look back and forth until they are satisfied. The images of the standard stimulus are presented four times each in a random order.

Five subjects participated in the study. The subjects were aged between 20 and 36, with normal or corrected-to-normal vision. They were given time to adapt to the dark environment, and they were asked to sit in front of the display at a normal viewing distance and angle. Fig. 8 illustrates the results. Each line represents the result for each of the three conditions. In this figure, a flat line supports the law of visual angle. A slope of 1 supports the law of size constancy. In the "Disk Lighting Alone with Reduction Tunnel" condition, the slope is -0.003 ± 0.006 (95% confidence interval). In the "Disk Lighting Alone" condition, the slope is 0.564 ± 0.071. In the "Disk and Corridor Lighting" condition, the slope is 0.639 ± 0.092. The analysis shows that as the presence of the depth information is increased, the observed effect of the depth on the size judgment increased from 0% ("Disk Lighting Alone with Reduction Tunnel" condition) to 64% ("Disk and Corridor Lighting" condition).

The results of the computer-modified experiment agree with the results of the classic experiment. The more contextual depth information is presented, the better the subject can gauge its location in a 3D environment. According to the size-distance invariance hypothesis, the perceived sizes of objects are derived from their perceived distances; subjects can estimate the actual size of the object based on its located distance. Therefore, it is concluded that:

- The size-distance relationship can be observed in the virtual environment generated by the perceptually based computer simulation.
- Perceptual studies can be effectively carried out in a computer environment, which provides advantages over the real world, because it allows for the control of variable manipulations.
- The indirect measurement of spatial depth is a feasible and practical methodology for computational perceptual studies on depth perception.

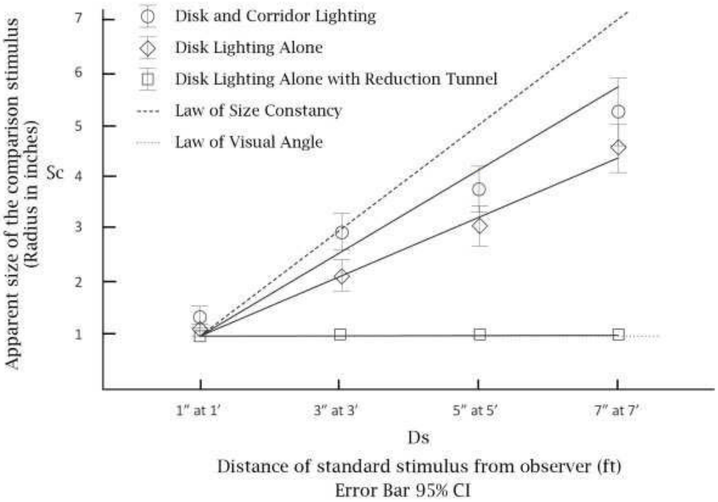


Fig. 8: Results of the computer-modified experiment.

3.3 Investigation on Scene-Based Luminance Distribution on Depth Perception

The experiment setup for Holway and Boring's classic study was adopted and modified to investigate the impact of luminance distribution on depth perception. As illustrated in Fig. 9, a corridor is divided into two hallways. At each hallway, there is a floating luminous disk of identical size (12" in radius) that serves as a visual target. The rear end of the corridor is open to admit daylight to illuminate the interior space. The experimental scenes were generated from the same viewpoint that is set towards the center of the corridor, and the disk floats at the center of each hallway in this perspective view. Two major variables are introduced into the experiment: the relative distance between the two disks was varied, and the architectural configurations were manipulated to create different lighting conditions between the two hallways (Tab. 2). In the "no skylight" condition, the scene was illuminated by the daylight admitted from the corridor's rear open end. In the "skylight at left" and the "skylight at right" conditions, an additional 5' × 10' skylight was installed 24' away from the viewpoint on the left and right hallways, respectively.

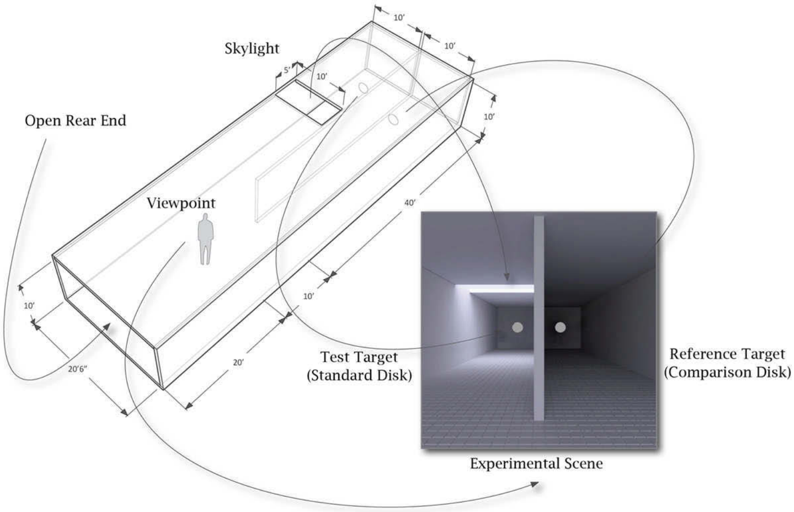
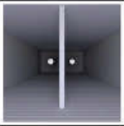
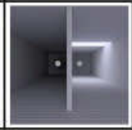
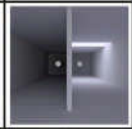
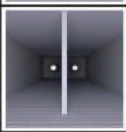
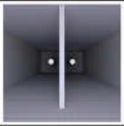
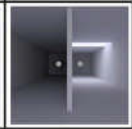
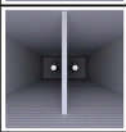
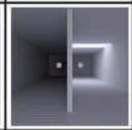
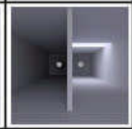
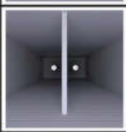
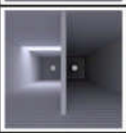
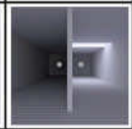
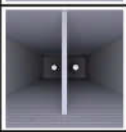
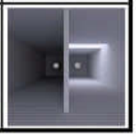


Fig. 9: Experiment setup.

The objective of this experiment is to investigate if the presence of additional lighting patterns would affect the perceptual judgment of spatial depth. The locations of both the right and left disks are varied to create 9 different relative distances. In scene "L0R," both disks are located 40' away from the viewpoint. In scene "L1r," the left disk was shifted 6" closer, while the right disk was shifted back 6" to create a 1' displacement. In the same manner, the left disk is 2', 3', and 4' closer than the right disk in scenes "L2r," "L3r," and "L4r," respectively. In scenes "l1R," "l2R," "l3R," and "l4R," the right and left disk are shifted to reversed positions and the right disk is 1', 2', 3', and 4' closer than the left disk, respectively. These nine configurations of disk locations are rendered with three different lighting conditions to generate a total of 27 experimental scenes, as illustrated in Tab. 2.

Relative distance between disks	Disk locations (Left, Right)	Conditions		
		Skylight at left	No skylight	Skylight at right
(L 4' r)	(38', 42')			
(L 3' r)	(38.5', 41.5')			
(L 2' r)	(39', 41')			
(L 1' r)	(39.5', 40.5')			
(L 0' R)	(40', 40')			
(l 1' R)	(40.5', 39.5')			
(l 2' R)	(41', 39')			
(l 3' R)	(41.5', 38.5')			
(l 4' R)	(42', 38')			

Tab. 2: Scenes from experiment.

The experiment scenes were rendered in HDR format (700x700 dpi) and tone-mapped with the photographic [25] and photoreceptor [26] tone-mapping operators to generate two sets of test images. The experiments were carried out in a dark room, and the images were displayed on the center of an LCD display. A total of eight subjects, aged between 21 and 36, participated in this study. Each had normal or corrected-to-normal vision, and was given time to adapt to the dark environment. The subjects were asked to sit in front of the display in order to view the image from a normal distance and angle. They were instructed that each scene incorporates two identical disks floating at the center of each hallway, and were asked to judge which disk appears to be closer. In each session, 27 images were shown in a random order 10 times, and the subject's responses were recorded as the number of times that the right disk is reported closer. Each subject performed the experiment twice with two different sets of tone-mapped images.

3.3.1 Results and Analysis

Perceptual studies on the evaluation of tone-mapping operators consistently show that the photographic tone-mapping operator performs well when compared to real physical scenes [3] [17]. The photoreceptor tone-mapping operator is a more recently developed algorithm that aims to model the photoreceptor behavior of a human's visual system [26]. The result of the paired sample t-test of the average of the numbers of right disks reported "closer" for each set of tone-mapped scenes shows that there is no statistical significant difference ($\alpha = 0.05$, two-tail, $t_{calc} = 1.846 < t_{crit} = 2.056$). It is thus concluded that the choice between the photoreceptor or photographic tone-mapping operator has an insignificant impact on the experiment results.

Fig. 10 illustrates the experiment results from the image set tone-mapped by the photographic tone-mapping operator. The subjects' responses are plotted as the proportion of the scenes in which the right disk is reported "closer" as a function of the right and left disks' relative distances. Probit regression curves provide an appropriate statistical method for modeling the regression of binary responses [7]. They are used to fit a cumulative distribution to each data set. The intersection points of each curve with the 50% proportion line are taken as the point of subjective equality (PSE). The PSE represents when the right and left disks are perceived equally in depth. The result demonstrates that in the "no skylight" condition, the two disks' distances were perceived to be equal when the two disks were configured at the same distance away (PSE = 0.03±0.01). In the "skylight at left" condition, in which the PSE was shifted to the left, the two disks were perceived to be equal in depth when the right disk was actually located 1.8 feet farther away than the left disk (PSE = −1.84±0.11). In the "skylight at right" condition, in which the PSE was shifted to the right, the two disks were perceived to be equal in depth when the right disk was actually relatively 2 feet closer (PSE = 2.12±0.11).

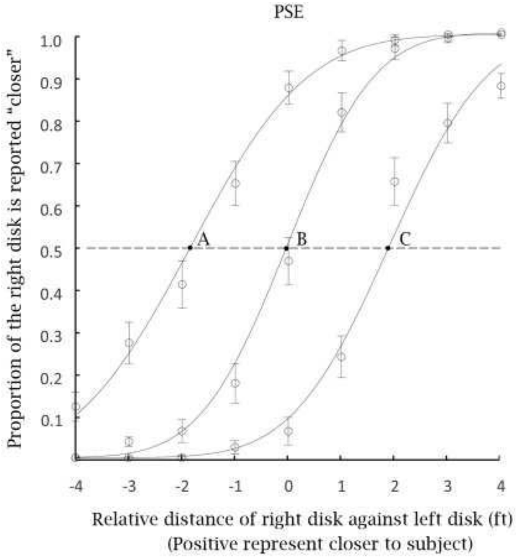


Fig. 10: Probit analysis: A is PSE with "skylight at left," B is with "no skylight," C is with "skylight at right."

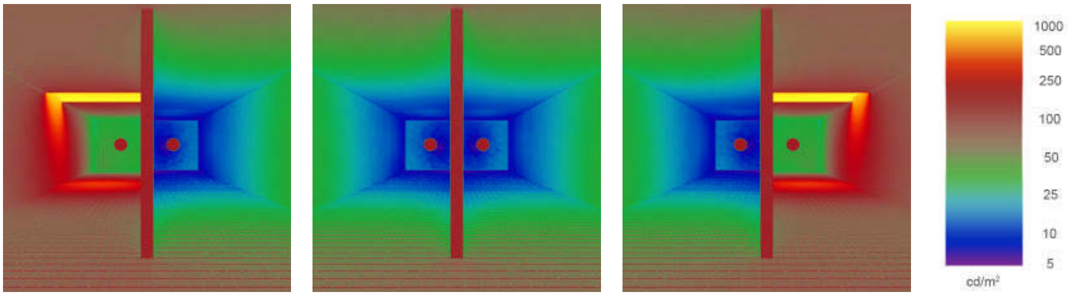


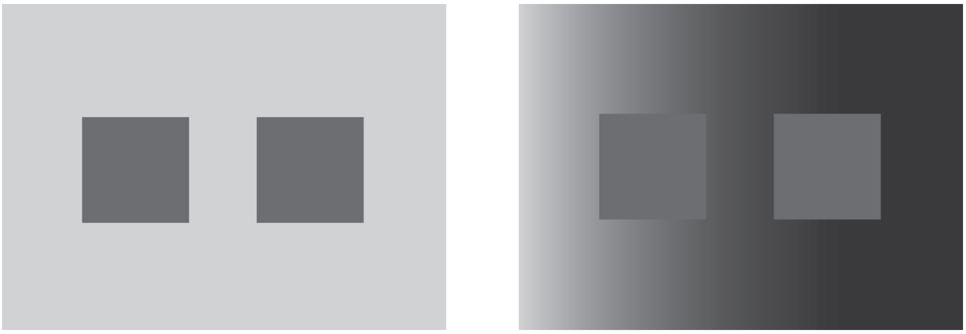
Fig. 11: False color studies of experimental scenes (left: “skylight at left” condition, middle: “no skylight” condition, right: “skylight at right” condition).

Fig. 11 illustrates the false color studies of the original high dynamic range scenes with the disks configured at the same locations under three lighting conditions. The luminance distributions of the two disks and their backgrounds were identical in the “no skylight” condition. In this base case, the perceived size is the main source to judge the perceived distance according to the size-distance relationship. The fact that PSE is 0.03 (expected value is 0) indicates that the subjects were able to judge the relative distance between the two disks accurately, based on the contextual information provided by the size-related pictorial depth cue.

However, the fact that PSE significantly shifted when the additional lighting pattern was presented suggests that the tone-related pictorial cue can influence the perceptual judgment of the spatial depth. The luminance contrast between the disk and its background was reduced when the hallway was illuminated by the additional skylight. In each instance, the right disk is perceived closer in the “skylight at left” condition, and the left disk is perceived closer in the “skylight at right” condition. These results are in agreement with the O’Shea et al. study (1983), which concluded that the higher the luminance contrast, the closer the target appears to be [20]. The additional skylight reduces the luminance contrast between the disk and its background, and thus increases its perceived distance.

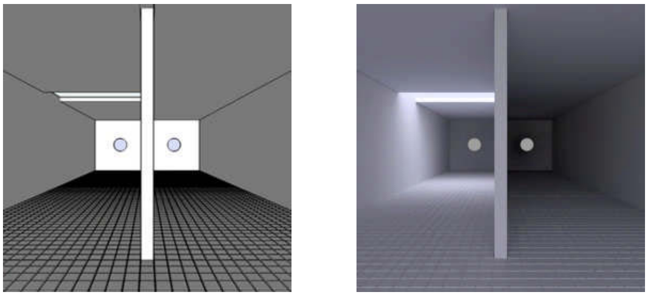
4 ENVISIONING SPATIAL EFFECTS OF TONE-RELATED PICTORIAL CUES IN COMPUTER SIMULATIONS

The visual mechanisms of lateral inhibition and chromatic light adaptation can cause patches with identical lightness scales to be perceived differently under different lighting conditions [21]. As illustrated in Fig. 12, the luminance of the four identical squares is perceived differently when presented with backgrounds of different luminance. The application of luminance contrast cues in architectural design thus requires a good method for accurately representing an un-built architectural scene.



(a) (b)

Fig. 12: Effect of background luminance on perceived brightness.



(a) (b)

Fig. 13: Comparison of the experimental scenes with different visual realism.

Fig. 13 illustrates the same experimental scene rendered with different degrees of visual realism. Fig. 13(a) is rendered with simple color and shade algorithms. Fig. 13(b) is rendered with a physically based rendering program, and tone-mapped by the perceptually based tone-mapping operator. In Fig. 13(a), the size-related pictorial cues available from the scene geometry provide dominant visual information to gauge the distance, and the two targets appear to be equal in depth. However, with the accurate lighting simulation, the effect of the luminance contrast on the perceived distance can be observed in Fig. 13(b). The light introduced from the skylight increases the dynamic range of the scene, and changes the luminance contrasts between the targets and their backgrounds. The two targets no longer appear to be located at the same distance away. Therefore, a scene simulation with a fair representation of the geometric layout can provide the necessary visual information to visualize the effect of size-related pictorial cues. On the other hand, to envision the spatial effect of a tone-related pictorial cue in a design process, the pictorial representation requires the perceptual realism of the physical scene.

5 CONCLUSIONS

Fig. 14 illustrates the relation of an architectural construction in a real space and its representations in a pictorial space. In a conventional representation, the perspective projection can represent the visual structure of the perceived geometry. Through orthographic and oblique projections, the geometry can be projected as a multi-view and a paraline view to depict the physical properties of the architectural construction. The linear perspective transforms the geometry from a conceptual view to a perceptual view. Various rendering techniques add color and tone to the established geometry that the renderer intends to convey to the audience. The complete set of representational techniques allows architects to configure an architectural construction from different conceptual views, and envision a perceptual view before the actual construction. These representations have thus been the platform that has mediated architectural design since the Renaissance. Computer modeling allows the geometry to be generated from graphical means as well as from numerical input, simplifying the process of constructing the geometry and allowing for the creation of complex forms. Computer rendering, powered by the computational capability of hardware and software, has advanced the visual realism of resultant imagery since its inception. The current computer-rendering techniques of physically based rendering and perceptually based tone mapping provide a possible solution for generating realistic pictorial representations of physical scenes. It bridges the gap of the perceptual equality of depth perception between the physical space and their representations in pictorial spaces.

This study demonstrates that the luminous environment of a 3D physical scene can be accurately simulated and represent as 2D imagery. It provides an alternative environment for conducting perceptual studies on tone-related pictorial cues that are restricted from the physical setting. Luminance contrast is identified as an effective depth cue. The perceptual realistic representation of a numerically accurate lighting simulation can also provide a pictorial environment for evaluating the application of this depth cue in the architectural design process. Architects can foresee the luminance distribution of the scene resulting from different configurations of architectural components, and can envision whether the resultant luminance contrasts can enrich the spatial experience of the proposed built environment.

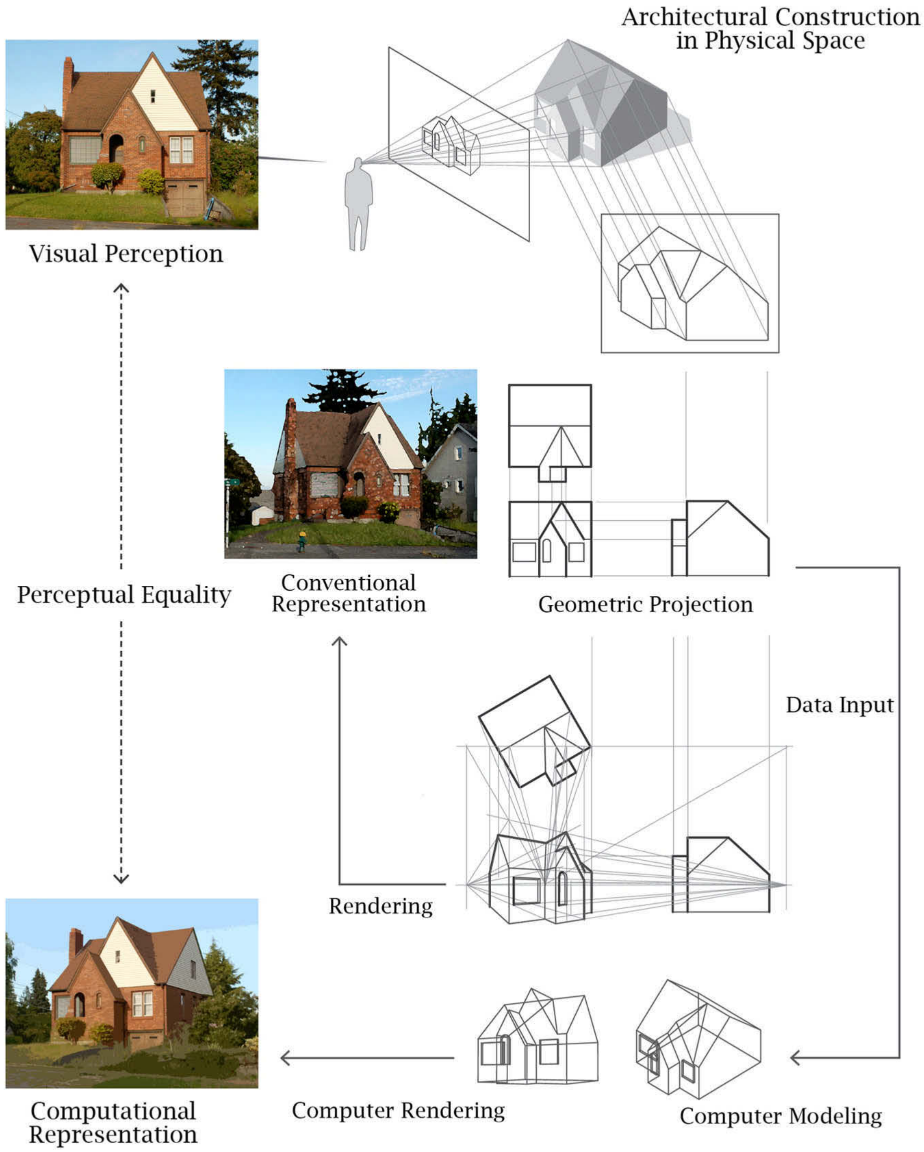


Fig. 14: Equality of perceptual reality of physical and pictorial spaces.

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