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TECHNICAL PAPER



Which visibility indicators best represent a population's preference for a level of visual air quality?

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ABSTRACT

Several studies have been carried out over the past 20 or so years to assess the level of visual air quality that is judged to be acceptable in urban settings. Groups of individuals were shown slides or computer-projected scenes under a variety of haze conditions and asked to judge whether each image represented acceptable visual air quality. The goal was to assess the level of haziness found to be acceptable for purposes of setting an urban visibility regulatory standard. More recently, similar studies were carried out in Beijing, China, and the more pristine Grand Canyon National Park and Great Gulf Wilderness. The studies clearly showed that when preference ratings were compared to measures of atmospheric haze such as atmospheric extinction, visual range, or deciview (dv), there was not a single indicator that represented acceptable levels of visual air quality for the varied urban or more remote settings. For instance, using a Washington, D.C., setting, 50% of the observers rated the landscape feature as not having acceptable visual air quality at an extinction of 0.19 km^{-1} (21 km visual range, 29 dv), while the 50% acceptability point for a Denver, Colorado, setting was 0.075 km^{-1} (52 km visual range, 20 dv) and for the Grand Canyon it was 0.023 km^{-1} (170 km visual range, 7 dv). Over the past three or four decades, many scene-specific visibility indices have been put forth as potential indicators of visibility levels as perceived by human observers. They include, but are not limited to, color and achromatic contrast of single landscape features, average and equivalent contrast of the entire image, edge detection algorithms such as the Sobel index, and just-noticeable difference or change indexes. This paper explores various scene-specific visual air quality indices and examines their applicability for use in quantifying visibility preference levels and judgments of visual air quality.

Implications: Visibility acceptability studies clearly show that visibility become more unacceptable as haze increases. However, there are large variations in the preference levels for different scenes when universal haze indicators, such as atmospheric extinction, are used. This variability is significantly reduced when the sky–landscape contrast of the more distant landscape features in the observed scene is used. Analysis suggest that about 50% of individuals would find the visibility unacceptable if at any time the more distant landscape features nearly disappear, that is, they are at the visual range. This common metric could form the basis for setting an urban visibility standard.

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Introduction

The human ability to see and appreciate objects or scenic vistas as viewed through the atmosphere or under water by the naked eye falls under the general term of “visibility.” Visibility of landscape features and objects is governed by the availability of light, its distribution on the object of regard and its background, the reflective properties of both, the image transmission characteristics of the intervening media, the properties of any magnifying and filtering optical devices employed, and the characteristics of the human visual system (Duntley et al. 1964; Malm 1979, 2016).

Written discussions concerning atmospheric optics and perceptions of sky color can be traced as far back as the ancient Greek civilization. Much of early photometry can be attributed to Bouguer (1760), who, in addition to other contributions, derived the exponential law of attenuation of a collimated beam of light and recognized quantitatively that the apparent brightness of an object is the sum of air-light and the attenuated image-forming information from some landscape feature of interest. In fact, he stated that if one looks carefully, a tree-covered mountain is visible if the difference between the brightness of the mountain and background sky is about 1 part in 50 or a

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contrast of 0.02. Lambert (1774) presented algebraic equations of these relationships.

It was not until the early 1900s that a renewed interest in visibility emerged when the aviator asked the meteorologist “How far can I see?,” which is also the title of a paper by Middleton (1935). Up until about 1970, visibility was mostly concerned with aircraft operations and the military’s need to identify and recognize targets from the air, the ocean, underwater, and, to some degree, space.

In the 1970s, the National Park Service (NPS) and other federal land-managing agencies were entrusted with the responsibility of preserving and protecting landscape features and the natural beauty of NPS units for the enjoyment of present and future generations. Part of this mandate is derived from the Clean Air Act (CAA 1977) and its amendments, which charge federal land managers of mandatory federal Class I areas to protect the air-quality-related values (including visibility) of the units under their jurisdiction. It was emphasized that visibility is more than being able to see an object at a distance at which the contrast reaches a threshold value. It also is the ability to clearly see and appreciate near and distant landscape features.

To this end, research generally shifted from studying the atmospheric effects on being able to see and detect objects or targets to the seeing and detecting of the haze itself and understanding how landscape features that are observed at distances less than the visual range change as a function of varying haze levels. Several studies were initiated to investigate relationships between human perception and values as a function of haze levels. The studies can be generally categorized into six areas of investigation: thresholds and supra-thresholds of uniform haze (Malm et al. 1987) and layered hazes (Henry 1977), including elevated haze layers or plumes; human judgments of visual air quality (VAQ) (Malm et al. 1981; Middleton et al. 1984; Stewart, Middleton, and Ely 1983); levels of visibility impairment judged to be unacceptable, known as visibility preference studies (Abt Associates 2001; AZ DEQ, 2003; Ely et al. 1991; Pryor 1996); scenic beauty estimates of landscape features as a function of haze levels (Latimer, Hogo, and Daniel 1981); the relative importance of visibility to park visitors and its effect on visitor satisfaction (Ross, Malm, and Loomis 1985; 1987) and behavior (Evans and Jacobs 1982; Evans et al. 1987; Evans, Jacobs, and Frager 1982; Rotton et al. 1979); and finally, the value that people put on good VAQ, either in monetary terms or in terms of the distribution of time spent in a park viewing scenic landscape features or exploring other park attributes

(Chestnut and Dennis 1997; Loehman, Park, and Boldt 1994; Smith et al. 2005).

In all the urban preference studies, the unacceptable/acceptable judgments of haze obscuring landscape features, when compared to atmospheric extinction or variables derived from atmospheric extinction such as visual range and deciview (dv), clearly indicate that none of these measures of atmospheric haze regularly gauge visibility preference levels. In the following discussion, visibility preference and visibility metrics are briefly reviewed, and a metric that best universally represents human preference for acceptable visibility is identified.

Visibility metrics

Visibility metrics fall into two broad categories: those that are scene dependent and those that are not. For the purposes of this discussion, they are referred to as scene-dependent and universal metrics, respectively. For a more complete discussion of visibility metrics as well as their relationships to extinction, the reader is referred to Malm (2016) and Malm et al. (2018). All universal visibility metrics are derivable from atmospheric extinction.

Universal metrics

The atmospheric extinction coefficient (b_{ext}), which is the sum of scattering and absorption per unit distance by particles and gases, is a measure of the alteration of radiant energy as it passes through the atmosphere. The effect of the atmosphere on the visual properties of distant objects theoretically can be determined if the concentration and characteristics of air molecules, particles, and absorbing gases throughout the atmosphere are known and, most importantly, are along the line of sight between the observer and object. The term b_{ext} is fundamental to the definition of all the other universal metrics.

The extinction coefficient has not been a popular visibility metric for the general public, who prefers the use of the seemingly easier to understand “visual range,” which has the additional advantage of using simple length units (e.g., miles or kilometers), while b_{ext} uses reciprocal length units.

To paraphrase Middleton (1960), when we see the blue of the distant hills, we deceive ourselves; what we really see is the blue of the air between the hills and our eyes. As our gaze travels from hill to hill into the distance, a point is reached where we cannot quite be sure—is it a hill, or the sky beyond? The air-light, or light between a landscape feature and observer, at this

point has come to be nearly (about 98%) as bright as the horizon-sky, the latter of which is, of course, all the air-light between us and empty space. With this in mind, daytime visibility (visual range) is defined as the distance at which an object becomes so nearly as bright as its background that we can no longer see its outline. Put another way, the contrast between object and background is then about 2% (-0.02). One of the properties of the human eye is that it cannot distinguish a contrast less than this.

A landscape feature at a distance equal to its visual range has lost all its inherent scenic beauty; it is just barely noticeable as some distant object. A more relevant visual range is the distance at which an observer can see and appreciate a landscape feature that is unimpaired by haze other than the naturally occurring background haze associated with air molecules. The distance at which a landscape feature can just be detected is referred to as the visual range (V_r), while the greatest distance at which an unimpaired landscape feature can be observed is referred to as unimpaired visual range (V_{ur}) (Malm 2016).

If the contrast threshold of the viewed landscape feature is taken to be -0.02 , the landscape feature is observed under uniform lighting conditions, and the haze is uniformly distributed, the relationship between atmospheric extinction and visual range is given by

$$V_r = 3.9/b_{ext} \quad (1)$$

where V_r and b_{ext} are expressed in consistent length and inverse length units, respectively. Given the same assumptions, unimpaired visual range is derivable from atmospheric extinction using

$$V_{ur} = 0.17/\Delta b_{ext} \quad (2)$$

where Δb_{ext} is the increase in extinction over some base or reference extinction such as Rayleigh scattering, the scattering of naturally occurring air molecules.

Because neither extinction nor the visual ranges just defined are proportional to perceived changes in VAQ, a scale was derived such that a change in the index would be perceived to be the same under any VAQ (haziness) condition, as long as there is a large, dark landscape feature at a distance proportional to $1/b_{ext}$. If the distribution of haze is uniformly distributed under uniform lighting conditions, the relationship between dv and b_{ext} is given by Pitchford and Malm (1994):

$$dv = 10 \left(\ln \frac{b_{ext}}{0.01 \text{ km}^{-1}} \right) \quad (3)$$

Here, 1 dv corresponds to about a 10% change in extinction, and 1 dv will be perceived to be approximately

constant under the assumptions of atmospheric and landscape feature conditions stated previously.

Scene-dependent visibility metrics

The above metrics are referred to as universal because they are not dependent on the distance from a landscape feature to an observer or on a landscape's inherent scenic qualities. As such, they are not expected to universally represent how varied landscapes are perceived. A given aerosol concentration will affect the appearance of each landscape differently, depending on its distance from the observer and its inherent scenic qualities. For example, an extinction of 300 Mm^{-1} will cause a Grand Canyon vista to disappear, while in a small room an extinction coefficient of 300 Mm^{-1} would go unnoticed.

The overarching goal of scene-dependent metrics is to relate human perceptions of the VAQ of a scene that is independent of observer-landscape feature distance or the inherent scenic qualities of the landscape feature. Some value of the metric would represent the same perceived VAQ, independent of the scene observed.

Haze can manifest itself either as layered or uniform haze. Layered haze can be thought of as any confined layer of particles or absorbing gas that results in a visible spectral discontinuity between that layer and its background (sky or landscape). Uniform haze exhibits itself as an overall reduction in air clarity. The classic example of a layered haze is a tight, vertically constrained, coherent plume (plume blight).

The eye is more sensitive to a sharp demarcation in brightness or color than it is to a gradual change in brightness or color, whether that change takes place in space or over time. Layered haze falls into the first category, in that the layer of haze is observed at some specific time and against some background (sky or landscape element), while uniform haze falls into the second. Because changes in uniform haze usually take place over time periods of hours or days, an evaluation of a VAQ change resulting from a uniform haze requires a person to "remember" what the scene looked like before a given change in air pollution took place. An evaluation of the impact a uniform haze has on VAQ requires identification of those elements of the total vista that are deemed important to a visitor's experience. On the other hand, a visible layered haze does not require remembering what the scene looked like at some past time but can be evaluated as an integral part of the scene at any specific time of observation. Even though layered hazes are not uncommon under stable atmospheric conditions, the preference studies discussed in the following section only address uniform haze.

Digital or film cameras can be used to capture the visual appearance of haze on landscape features. The image is a two-dimensional array, referred to as pixels, of film densities or digitized voltages, in three color channels, that are proportional to the image radiance field. The following discussion assumes film densities or pixel voltages have been calibrated to represent atmospheric radiance levels.

The ratio of the brightness (B) or radiance (N) of an object to the brightness or radiance of its background in the direction of observation, or some function of that ratio, is referred to as ratio contrast. Any function of this ratio is some form of contrast; however, this ratio minus 1 is the form of contrast used most often in visibility literature. If the object is dark and viewed against a background sky, the contrast is negative and can never be less than -1 , whereas if the object is brighter than the background sky, the contrast is positive and does not have a mathematical limit.

Apparent contrast is defined as

$$C_r = {}_1N_r / {}_2N_r - 1 = ({}_1N_r - {}_2N_r) / {}_2N_r \quad (4)$$

where ${}_1N_r$ and ${}_2N_r$ refer to the radiance associated with landscape features 1 and 2 that are at some distance r from an observation point. This contrast equation can be used to describe the visibility of a contrast edge either of a contiguous landscape feature or of a landscape feature as seen against a background sky.

Under uniform lighting conditions, when an object is viewed against the background sky, C_r is related to C_o , the inherent contrast of the object ($r = 0$), and atmospheric transmittance by $C_r = C_o T_r$, the familiar Koschmieder relationship (Koschmieder 1924).

Another possible contrast visibility index is the overall average image contrast and equivalent contrast, defined as

$$\bar{C} = \frac{\sum_i |(\bar{N}_r - N_{r,i})| / N'}{\bar{N}_r} \quad (5)$$

and

$$C_{eq} = \frac{\sqrt{2 \sum_{i=1}^{N'} (\bar{N}_r - N_{r,i})^2 / N'}}{\bar{N}_r} \quad (6)$$

where $\bar{N}_r$ and $N_{r,i}$ are the average scene radiance and the pixel-by-pixel radiance of each image element of the scene, respectively, and N' is the total number of pixels. Equivalent and average contrast are similar and highly correlated in that they are both proportional to the average deviation of pixel radiance values from the overall mean radiance level. The equation under the

square root sign in eq 6 is often referred to the mean square radiance fluctuation.

The radiance difference between adjacent pixels is attenuated in direct proportion to the atmospheric transmittance over the path between the landscape features represented by the pixels and the observer (Duntley et al. 1964; Malm 2016). The radiance difference between adjacent pixels can be estimated by a gradient operator applied to an image of interest. The average radiance difference associated with any given image then becomes an index that is proportional to the amount of haze present when the photo was taken.

One of the more popular gradient operators is the Sobel filter. Others, such as the Roberts, Scharr, and Prewitt operators, are similar, but all essentially identify the areas of an image with a change or gradient in the image radiance field (Malm 2016). The edges identified by these various operators and associated with various landscape features in the image are attenuated in direct proportion to the amount of haze in the atmosphere and the distance between the camera and landscape feature corresponding to the edge at the time the photo was taken. The visibility index is usually taken to be the average of the pixel values of the filtered image.

Another approach to identifying radiance difference edges is through the use of the fast Fourier transform (FFT). The FFT transforms the spatial variations in a radiance field into a spatial frequency domain usually referred to as $F(u, v)$, where u and v are the discrete spatial frequency variables (Malm 2016). By truncating $F(u, v)$ to higher spatial frequencies and then inverting back to x and y space, it is possible to extract only the edges of the embedded landscape features, essentially accomplishing the same thing as the gradient filters discussed earlier. Again, the visibility index is taken to be the average of the pixel values of the inverted, filtered image. The advantage of the FFT approach is that the analyst, by selecting the frequency domain to be considered, has some control over the “sharpness” of the edges used in the analysis.

One concept, although not explored in this article, that has evolved as a possible visibility metric to characterize visibility impairment is the just-noticeable difference or change (JNC) index (Carlson and Cohen 1978; Henry 1977, 1979; Malm and Pitchford 1989). A JNC refers to the minimum change in visual stimuli that causes the physiological and psychophysical response in the human visual system that is just noticeable when two stimuli are viewed side by side.

The metrics discussed above can be extended to perceptions of color. However, color metrics are beyond the scope of the analysis presented here. The reader interested in color metrics as applied to visibility issues is referred to

Latimer and Ireson (1980), Malm, Leiker, and Molenar (1980), Henry (1986), Horvath, Gorraiz, and Raimann (1987), Matamala and Henry (1990), and Ibraheem et al. (2012).

Visibility preference studies

There have been six urban and two nonurban visibility preference studies to date, five urban studies carried out in North America cities and one in Beijing, China, and two nonurban studies in North America (Malm 2016). Another study (Smith 2013) focused on the validity of the preference study approach in identifying levels of acceptable visibility. Smith (2013) presents an insightful review of the underpinnings of preference studies. She points out that “preferences” are defined as the ordering of all combinations (or “bundles”) of goods that people could experience or consume such that any combination that ranks higher than another combination generates higher utility or welfare (Hicks 1956; Samuelson 1938).

All eight visibility preference studies used a focus-group method to estimate the level of visibility impairment that respondents described as acceptable. The specific definition of “acceptable” was largely left to each individual respondent, allowing each to identify their own preferences. There are six completed studies that used this method and two pilot studies (designed as survey instrument development projects) that provide additional information. The completed studies were conducted in Denver, Colorado (Ely et al. 1991), two cities in British Columbia, Canada (Pryor 1996), Phoenix, Arizona (AZ DEQ (Arizona Department of Environmental Quality) 2003), Beijing, China (Fajardo, Jiang, and Hao 2013), and Great Gulf Wilderness, New Hampshire (Hill et al. 2000). The two pilot studies were conducted in Washington, D.C. (Abt Associates 2001), and Grand Canyon, Arizona. The Grand Canyon survey results are presented here for the first time. The studies are summarized in Table 1. The Beijing study, although discussed below, is not included in Table 1 because all the information included in the table was not available in the published journal article (Fajardo, Jiang, and Hao 2013). Actual photos of various images used in these studies can be found in Malm (2016) and Malm et al. (2018).

In each study, information was collected in a focus-group setting, where photographic slides or hardcopy photos depicting various visibility conditions were presented. In the urban studies, slides of a single scene from the study’s city were used; each slide included images of the broad downtown area and out to the hills or mountains composing the scene’s backdrop. The Grand Canyon view was looking west down the

canyon, while the Great Gulf scene was of a nearby notch looking out toward a 7-km-distant knoll.

The maximum sight distance under good conditions varied by city, ranging from 8 km in Washington, D.C., to mountains more than 100 km away in Denver. The Grand Canyon scene included a view of the 100-km-distant Mount Trumbull, which is a small “bump” on the distant horizon, and a more prominent 35-km cliff wall, as well as many less distant landscape elements. The Great Gulf scene essentially consisted of a nearby 7-km-distant landscape feature. Multiple photos of the same scene were used to present approximately 20–30 different levels of visibility impairment.

Actual photographs taken in the same location over several years were used in the Denver, British Columbia, and Grand Canyon studies to depict various visibility conditions. The photos used for the Grand Canyon study came from the NPS air quality webcam network (<https://www.nature.nps.gov/air/webcams>). The photos included varying lighting conditions due to the time of day and changing meteorological conditions. Photographs prepared using WinHaze software (Air Resource Specialists, Inc., <https://www.air-resource.com/resources/downloads.html>) were used in the Phoenix, Washington, D.C., and Great Gulf studies. WinHaze is a computer imaging software program that simulates VAQ differences of various scenes, allowing the user to “degrade” an original, near-pristine-condition visibility photograph to create a photograph of each desired VAQ level.

Denver, Colorado, urban visibility preference study

The Denver urban visibility preference study was conducted on behalf of the Colorado Department of Public Health and Environment. A series of focus-group sessions was conducted with 17 civic and community groups, in which a total of 214 individuals were asked to rate slides. The slides depicted varying levels of VAQ for a well-known Denver vista, including a broad view of downtown Denver, with the mountains to the west composing the scene’s background.

The participants were instructed to base their judgments on three factors:

- (1) The standard was for an urban area, not a pristine national park area where the standards might be stricter.
- (2) The level of an urban visibility standard violation should be set at a VAQ level considered to be unreasonable, objectionable, and unacceptable visually.
- (3) Judgments of standards violations should be based on visibility only, not on health effects.

Table 1. Summary of visibility preference studies.

	Denver	Phoenix	British Columbia	Washington, DC	Grand Canyon	Great Gulf
Report date	1991	2003	1996	2001	2017	1996
Session duration	??	45 min	50 minutes	2 hours	1 hour	??
Compensation	None	\$50	None	\$50	None	None
Number of focus-group sessions	17	27 total at 6 locations	4	1	1	3
Number of participants	214	385	180	9	9	300
Age range	Adults	18–65+ years	University students	27–58 years	Adults	Adults
Annual or seasonal	Winter	Annual	Summer	Annual	Summer	Summer
Number of total scenes presented	Single scene of downtown with mountains in background at about 60–130 km	Single scene of downtown and mountains, 42 km maximum distance	Single scene from each city with distant mountains at about 30 km	Single scene of DC Mall with 8-km maximum sight path	Single scene of Grand Canyon with most distant mountains at 100 km —prominent ridge 35 km	Single scene of Mt. Jefferson with most distant mountain about 7 km
Number of total visibility conditions	20 levels (+ 5 duplicates)	21 levels (+ 4 duplicates)	20 levels (10 each from each city)	20 levels (+ 5 duplicates)	30 levels (+ 1 duplicate)	23 levels
Source of slides	Actual photos taken between 9 a.m. and 3 p.m. Medium of presentation	WinHaze	Actual photos taken at 1 p.m. or 4 p.m. Slide projection	WinHaze	Webcam images (noon)	WinHaze and actual photos
Slide projection	Slide projection	Slide projection	Computer image projection	5x7 photos and computer image projection		
Ranking scale used	7-point scale	7-point scale	7-point scale	7-point scale	7-point scale	5-point scale
Extinction level presented	0.03–0.65 km ⁻¹	0.055–0.341 km ⁻¹	0.037–0.195 km ⁻¹ (Chilliwack) 0.046–0.234 km ⁻¹ (Abbotsford)	0.034–0.471 km ⁻¹	0.01–0.063 km ⁻¹	0.01–0.545 km ⁻¹
Health issue directions	Judge solely on visibility; do not consider health	Judge solely on visibility; do not consider health	Judge solely on visibility, do not consider health	Health never mentioned; “focus only on visibility”	Health never mentioned; “focus only on visibility”	Judge solely on visibility; do not consider health
Key questions asked	a) Rank VAQ (1–7 scale) b) Is each slide “acceptable” c) “How much haze is too much”	a) Rank VAQ (1–7 scale) b) Is each slide “acceptable” c) How many days a year would this picture be “acceptable”	a) Rank VAQ (1–7 scale) b) Is each slide “acceptable”	a) Rank VAQ (1–7 scale) b) Is each slide “acceptable” c) If this haze, how many hours would it be acceptable (3 slides only) d) Valuation question	a) Rank VAQ (1–7 scale) b) Is each slide “acceptable”	a) Rank order photos according to visibility conditions b) Is each slide “acceptable” c) Valuation question
Mean b _{ext} found “acceptable”	0.075 km ⁻¹ (20.1 dv)	0.14 km ⁻¹ (26 dv)	0.11 km ⁻¹ (~ 24 dv) (Chilliwack), 0.11 km ⁻¹ (~ 24 dv) (Abbotsford)	0.19 km ⁻¹ (~ 29 dv)	0.02 km ⁻¹ (~ 7 dv)	0.074 km ⁻¹ (~ 20 dv)

Participants were shown 25 randomly ordered slides of actual photographs. The visibility conditions presented in the slides ranged from 11 to 41 dv, approximating the 10th to 90th percentiles of wintertime visibility conditions in Denver. The corresponding haze conditions varied from very clear to levels where the distant mountains were totally obscured and the downtown buildings nearly obscured. Foreground features were highly visible. The participants rated the 25 slides based on a scale of 1 (poor) to 7 (excellent), with 5 duplicates included. They were then asked to judge whether the slide would violate what they would consider to be an appropriate urban visibility standard (i.e., whether the level of impairment was acceptable or unacceptable).

Phoenix, Arizona, urban visibility preference study

The Phoenix urban visibility preference study was conducted on behalf of the Arizona Department of Environmental Quality. Its focus-group survey process was patterned after the Denver study. The study included 385 participants in 27 separate focus-group sessions. Participants were recruited using random-digit dialing to obtain a sample group designed to be demographically representative of the larger Phoenix population. Focus-group sessions were held at six neighborhood locations throughout the metropolitan area to improve the participation rate. Participants received \$50 as an inducement to participate.

Participants were shown a series of 25 images of the same vista of downtown Phoenix, with South Mountain in the background at about 40 km. Photographic slides of the images were developed using WinHaze so that the only variation from slide to slide was due to varying haze levels. The lighting and meteorological conditions were kept constant. The visibility impairment levels ranged from 15 to 35 dv (the extinction coefficient, b_{ext} , range was approximately 55 Mm^{-1} to 340 Mm^{-1}). The resulting haze conditions varied from very clear to levels where the distant mountains were totally obscured and the downtown buildings nearly obscured. Foreground features were highly visible. First, participants individually rated the randomly shown slides on a VAQ scale of 1 (unacceptable) to 7 (excellent). Participants were instructed to rate the photographs solely on visibility and to not base their decisions on either health concerns or what it would cost to have better visibility. Next, the participants individually rated the randomly ordered slides as “acceptable” or “unacceptable,” defined as whether the visibility in the slide was acceptable or objectionable.

British Columbia, Canada, urban visibility preference study

The British Columbia (BC) urban visibility preference study was conducted on behalf of the BC Ministry of Environment. Focus-group sessions were conducted that were also developed following the methods used in the Denver study. Participants were students at the University of British Columbia who participated in one of four focus-group sessions with between 7 and 95 participants. In total, 180 respondents completed surveys (29 did not complete the survey). Participants in the study were shown slides of two suburban locations in BC: Chilliwack and Abbotsford. Abbotsford (population 130,000) is an ethnically diverse suburb adjacent to the Vancouver metro area, while Chilliwack (population 70,000) is an agricultural community 100 km east of Vancouver in the Frazier Valley.

The dv ranges were 13–29 for Chilliwack and 15–31 for Abbotsford. The resulting haze conditions for the observed scenes varied from clear to levels where the distant mountains were totally obscured, and foreground features were always highly visible.

Washington, D.C., urban visibility pilot preference study

The Washington, D.C., urban visibility pilot study was conducted on behalf of the U.S. Environmental Protection Agency (EPA) and was designed to be a pilot focus-group study, an initial developmental trial run of a larger study. The intent of the pilot study was to study both focus-group method design and potential survey questions. Due to funding limitations, only a single focus-group session was held, consisting of one extended session with nine participants. The study also adopted the general Denver study method, modifying it as appropriate to be applicable in an Eastern urban setting that has substantially different visibility conditions than any of the three western locations of the other preference studies. Washington’s (and the entire East) visibility is typically substantially worse than Western cities and has different characteristics. Washington’s visibility impairment is primarily a uniform, whitish haze dominated by sulfates, relative humidity levels are higher, the low-lying terrain provides substantially shorter maximum sight distances, and many residents are not well informed that anthropogenic emissions impair visibility on hazy days.

A single scene was used: a panoramic shot of the Potomac River, Washington Mall, and downtown Washington, D.C. As in the Phoenix study,

photographic slides of the images were developed using WinHaze so that the only variation from slide to slide was due to varying haze levels. The lighting and meteorological conditions were kept constant. The dv range used was 9–38, which corresponds to an extinction range of about 34–471 Mm^{-1} . The resulting haze conditions for the observed scenes varied from quite clear to levels where the most distant landscape features were totally obscured, while foreground features for the most part remained unchanged.

Beijing, China, urban visibility preference study

Fajardo, Jiang, and Hao (2013) report on a visibility preference study carried out using Beijing, China, urban scenes and funded by various government agencies in China. Unfortunately, the publication does not include an image of the scene characteristics or the distances to various landscape features. The protocol used was similar to those used in the urban preference studies already discussed. The survey was conducted at a middle school located in the Shunyi District, and the participants were seniors between the ages of 15 and 18 years. The survey presented photographs to 85 individuals of a single scene ranging from 15 to 51 dv. The images were rated for VAQ on a 1 to 7 scale, and the participants were told not to consider related air pollution health effects. Next, the students were asked to determine whether a given level of haze was unacceptable.

Grand Canyon, Arizona, visibility preference pilot study

Initial VAQ judgment studies at Grand Canyon National Park were carried out in the late 1970s and 1980 and were reported on by Malm et al. (1981). Those earlier studies focused only on judgments of VAQ, and the images used were carefully selected to ascertain how lighting conditions, changing foreground size and color, and meteorological conditions affected VAQ judgments. They did not, however, address visitor acceptability of a given level of haziness.

The intent of the Grand Canyon pilot study was to explore judgments of acceptable haze levels in a pristine visual environment under all types of viewing conditions, including obscuration by naturally occurring phenomenon such as rain and clouds.

The study also adopted the general Denver study format and, as with the Washington, D.C., pilot study, nine participants from the Colorado State University atmospheric research staff participated. The dv range of 30 slides was 3–20 dv or about 13–63 Mm^{-1} of

extinction. A single scene looking west down the canyon with a small landscape feature of a 100-km-distant mountain (Mount Trumbull) and many closer landscape features ranging from 35 to 1 km was used. At 3 dv, the scene is nearly free of haze, and because images were taken under naturally occurring conditions, in a few photos all landscape features were obscured because of clouds.

First, participants individually rated the randomly shown slides on a VAQ scale of 1 to 7. Participants were instructed to rate the photographs solely on visibility and to not base their decisions on either health concerns or what it would cost to have better visibility. Next, the participants individually rated the randomly ordered slides as “acceptable” or “unacceptable,” defined as whether the visibility in the slide was acceptable or objectionable.

Great Gulf Wilderness, New Hampshire, visibility preference study

This study was conducted over concerns of visibility degradation in the White Mountains of New Hampshire and was partially supported by the White Mountain National Forest agency (Hill et al. 2000). The objective of the study was to understand visibility conditions in the Great Gulf Wilderness, the sensitivity of visitors to haze, and the economic value of potential visibility changes to visitors. The protocol used was similar to those used in the urban preference studies already discussed. The goal of the study was to by survey determine (1) whether forest visitors could consistently distinguish, rate, and rank photographs of a spectrum of visibility conditions; (2) whether respondents perceived visual range as unacceptable at some consistent value when viewing clear to haze-obscured vistas of Mount Jefferson in the Great Gulf Wilderness; and (3) the value of the change in visibility. Three sets of duplicate photos in a series of 23 photographs were used, with dv ranging from about 1 to 40 dv ($b_{ext} = 0.02\text{--}0.545 \text{ km}^{-1}$). The farthest vista element, which made up about one-third of the scene, was only 7 km distant and was nearly obscured at 40 dv.

Results

Relationship between VAQ and acceptability judgments

Images and concurrent ratings were not available for the Beijing and Great Gulf Wilderness studies so are not included in the following analysis. The VAQ judgment metric is a direct measure of a person's response to haze effects on a scene. VAQ judgments of changes

in landscape feature color and lightness are all proportional to the integrated b_{ext} or particulate mass over the sight path between the observer and landscape feature as well as changing lighting and meteorological conditions. In all five urban and the Grand Canyon preference studies, VAQ ratings were made along with visibility acceptability judgments.

Figure 1 shows a scatter plot of the percent of observers judging an urban scene to have acceptable VAQ as a function of judged VAQ for each of the studies described above: Washington, D.C. (WASH), Phoenix, Arizona (PHX), Chilliwack, BC (CHIL), Abbotsford, BC (ABBT), Denver, Colorado (DEN),

and Grand Canyon (GRCA). Notice that the shape of the curves representing each of the studies is the same. When asked to judge VAQ, participants distributed their ratings across the images they were shown, but when the participants were asked to judge acceptability, there tends to be a level of VAQ that is acceptable and one that is not acceptable. In all cases, VAQ ratings above 5 were judged to be acceptable by more than 50% of the participants and VAQ ratings below 3 to be unacceptable by more than 50% of the participants.

For all six locations, the VAQ judgments were made on a 1–7 scale, resulting in a median rating of 4. Figure 2 shows a plot of the fraction of the VAQ ratings

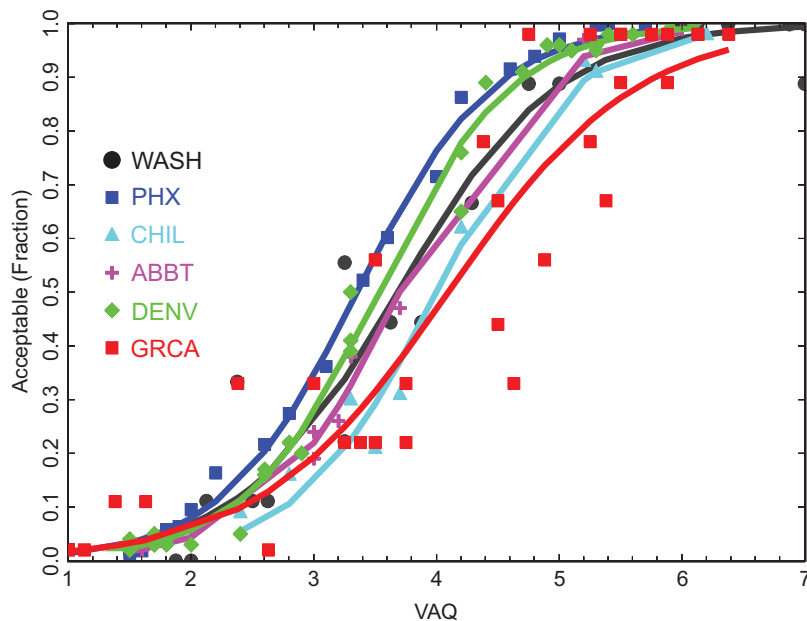


Figure 1. Scatter plot of the percent of observers judging an urban scene to have acceptable visual air quality (VAQ) as a function of judged VAQ for each of the studies described in the text.

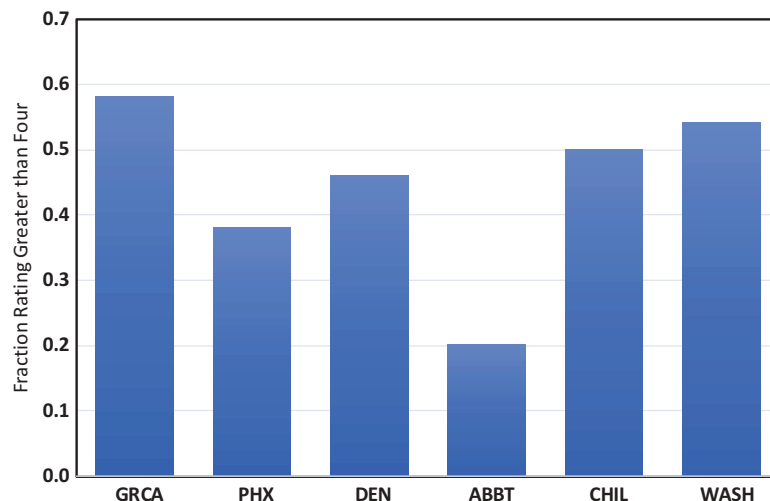


Figure 2. Fraction of VAQ ratings greater than the median value of 4.

that were greater than 4 for each of the study locations. It might be expected that because slides from all study locations represented a full range of visibility conditions from near-Rayleigh or very clear to very hazy, the average VAQ would be about 4. Figure 2 shows this clearly is not the case. All urban scenes were rated less than 4 more frequently than the GRCA scene, even though the GRCA series of slides included some images in which the entire scene was obscured. For the Grand Canyon scene, about 60% of the images were rated greater than 4, while only 20% of the images were judged greater than 4 at ABBT. Less than 40% of the images were rated greater than 4 for the PHX scene. Apparently, those scenes with inherently higher scenic quality invoke higher VAQ judgments.

In Figure 3, the fraction of participants who judged the urban scene acceptable for a VAQ rating of 4, along with an upper and lower uncertainty limit that corresponds to one standard error of a regression between measured and predicted acceptability levels, is shown. Notice that the uncertainty is greatest for WASH and GRCA, where there were only nine observers participating. With a median VAQ judgment of 4, all but one of the urban scenes were found acceptable by more than 60% of the respondents, with the one outlier being CHIL. Within the uncertainty of ± 1 standard error, the DEN, WASH, and ABBT acceptable ratings are the same, at about 0.65, for a VAQ judgment of 4, while the PHX acceptability rating is somewhat higher at 0.75 and CHIL a bit lower at about 0.5. The acceptability fraction for GRCA was about 0.45.

Clearly, judging overall VAQ and making a judgment as to what level of haze is acceptable or unacceptable evoked a different response in participants. For the GRCA scene,

even though about 60% of the images shown to observers were rated to have VAQ levels above the median value of 4, only about 45% found a rating of 4 acceptable, whereas for the PHX scene, less than 40% of the images were judged to have VAQ levels greater than 4, but more than 75% found a scene with a rating of 4 acceptable. In general, scenes that had lower VAQ ratings corresponded to higher levels of acceptability of haze.

Which visibility metrics best reflect an observer's acceptability of a given haze level?

This section explores which of the many image metrics best reflect observer-judged acceptability of a level of haze and ultimately relate the metric to atmospheric extinction and PM levels. Table 2 summarizes the correlation between the fraction of observers who judged an image to be acceptable and atmospheric extinction, monochromatic average contrast, Sobel index, and apparent sky-image contrast of the more distant landscape feature. Deciview and visual range are not shown because they are both derived from extinction, so the correlation between them and acceptability judgments are the same as for extinction. Average and equivalent contrast are derived in a similar way, so correlations between acceptability and equivalent contrast are the same as for acceptability and average contrast. The correlation between all edge detection metrics and acceptability is nearly the same, so only the Sobel index is shown in Table 2. Image color metrics were not explored.

The WASH and PHX images were created with the WinHaze model, so the only alteration in appearance as a function of haze level is due only to haze and not lighting condition changes, which result from changing time of

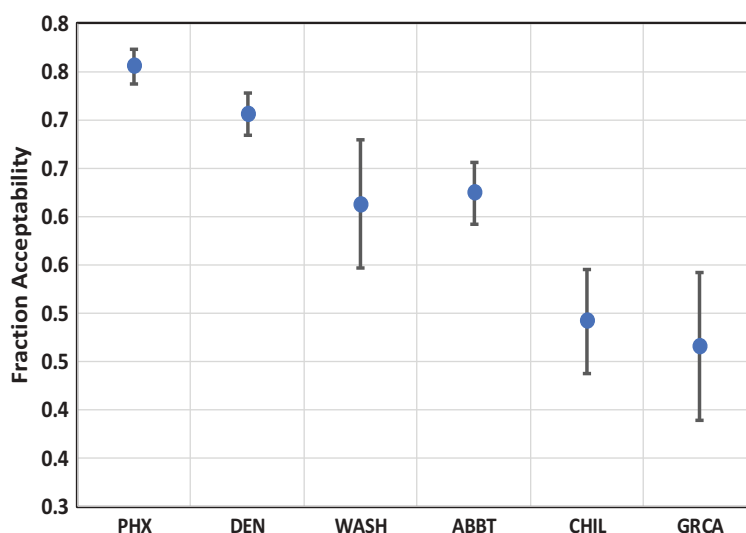


Figure 3. Fraction of study participants who rated the respective landscapes as acceptable at a VAQ = 4.0. The bars represent 1 standard error uncertainty.

Table 2. Correlations of average acceptability ratings with various visibility metrics.

Metric	b_{ext}	$\bar{C}$	SOB	C_r
Washington	-0.93	0.93	0.93	-0.90
Phoenix	-0.91	0.96	0.96	-0.92
Denver	-0.73	0.43	0.42	-0.69
Chilliwack	-0.87	0.04	0.31	-0.76
Abbotsford	-0.86	-0.09	-0.02	-0.93
Grand Canyon	-0.74	0.36	0.68	-0.74

day or meteorological conditions, including cloud cover, or from changing foreground conditions that frequently occurred in urban scenes. The ABBT photos were taken with an airport taxiway in the foreground, so images have foreground elements that consist of varying types of aircraft. These image conditions are reflected in the correlations between acceptability and the image metrics presented in Table 2. All metrics are well correlated with acceptability for WASH and PHX images but not for the DEN, CHIL, ABBT, and GRCA images, which were taken over time and in natural ambient settings. Also, for the WASH and PHX images, all metrics are well correlated with each other but not with the other study areas. Correlations tend to be higher between acceptability and atmospheric extinction and also with the more distant apparent sky-landscape feature contrast, C_r . Figure 4 shows the same acceptability data as in Figure 1, plotted against the atmospheric extinction associated with the various haze levels. A logistical regression model, applied to each data set, was used to estimate the acceptability levels summarized in Table 3.

The Beijing and Great Gulf studies are not summarized in Figure 4 and Table 3 because the physical characteristics of the scenes used in those studies and the distribution of extinction levels of the slides used in the studies are not known. Fajardo, Jiang, and Hao (2013) did report that extinction levels of 300–900 Mm^{-1} (~ 100 –300 $\mu g\ m^{-3}$) were required for 50% of the participants to judge the Beijing scene used as unacceptable. In the Great Gulf acceptability study, they found an extinction level of 74 Mm^{-1} ($25\ \mu g\ m^{-3}$) caused 50% of the participants to judge the scene to be unacceptable. Approximate mass concentrations are determined assuming particles have a mass extinction coefficient of 3 m^2/gm and are not hygroscopic.

Table 3 illustrates that it takes considerably more atmospheric extinction, or particulate concentration, to cause the Washington, D.C., scene to be judged unacceptable than the GRCA scene. This is also true whether extinction is expressed in terms of dv or visual range, since these two variables are directly derivable from extinction. The amount of extinction required for 50% of observers to have an unacceptable judgment for WASH is 192 Mm^{-1} ($61\ \mu g\ m^{-3}$), while for GRCA it is only 23 Mm^{-1} ($4.3\ \mu g\ m^{-3}$).

The amount of extinction required for other scenes to be judged as unacceptable is intermediate to WASH and GRCA. Even though the GRCA scene shows a greater preference versus VAQ sensitivity than the WASH scene, the primary cause of the significant difference in extinction to preference relationship between

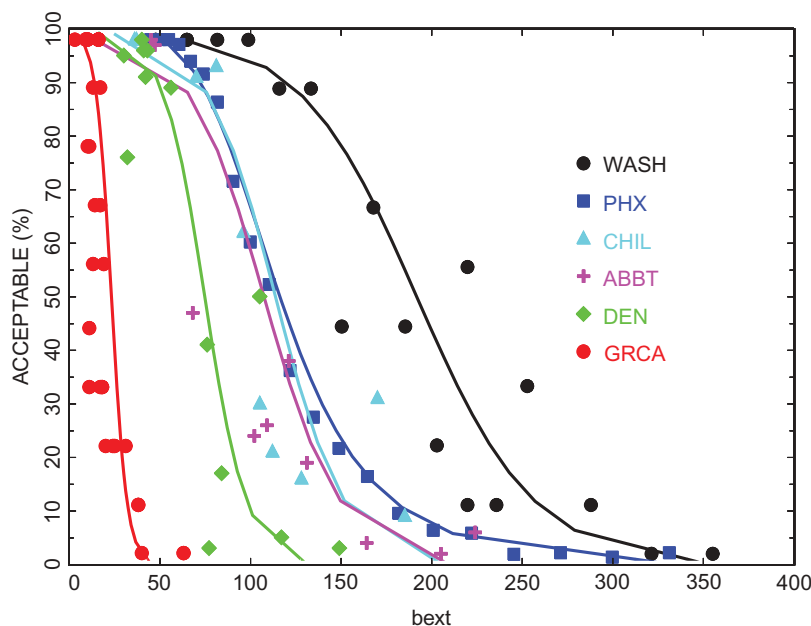
**Figure 4.** Percent acceptability levels plotted against atmospheric extinction for each of the images used in the various studies.

Table 3. Percentile acceptability levels and associated uncertainties, expressed in atmospheric extinction terms of Mm^{-1} , for each of the scenes studied.

Percentile acceptability	10%	25%	50%	75%	90%
Washington	263.1 ± 1.0	227.5 ± 1.0	191.8 ± 0.7	156.1 ± 0.6	120.4 ± 0.4
Phoenix	186.4 ± 1.5	147.2 ± 1.3	116.2 ± 1.0	91.8 ± 0.8	72.5 ± 0.6
Denver	100.1 ± 2.4	87.4 ± 2.1	74.8 ± 1.7	62.1 ± 1.4	49.4 ± 1.0
Chilliwack	155.5 ± 2.1	134.7 ± 1.8	113.8 ± 1.5	93.0 ± 1.2	72.2 ± 0.9
Abbotsford	153.7 ± 2.3	130.6 ± 1.9	107.5 ± 1.6	84.4 ± 1.3	61.2 ± 1.0
Grand Canyon	32.6 ± 2.3	27.9 ± 2.0	23.2 ± 1.7	18.5 ± 1.3	13.8 ± 1.0

the two sites is the distance to the landscape features. Most features in the GRCA scene are 10+ km distant, while landscape elements in the WASH scene are only a few kilometers distant, with foreground features only meters distant.

In the Beijing study, the level of haze required to cause 50% of the participants to find the scene unacceptable is 2–5 times greater than in the WASH study. The higher extinction levels to evoke an “unacceptable” response from survey participants could be a result of a more urban scene, with most dominant landscape features being only meters or a kilometer or two distant. It is also possible that the participants in the study were accustomed to and accepting of the lower visibility levels normally found in Beijing.

It should not be surprising that there is not a single level of atmospheric extinction that represents a given acceptability level. Extinction is a measure of light attenuation and scattering over a unit distance (a single point in space); however, visible haze is equally dependent on extinction and distance to a landscape feature, so every feature, being a different distance from the observer, will have its own sensitivity to changes in atmospheric mass concentration or extinction. Extinction alone is not representative of haze.

Is there a metric that has the same value for a given acceptability level? The index must not only correlate with acceptability ratings but have the same value for different preference levels, independent of the scene being observed. Metrics that depend on pixel-to-pixel comparisons such as contrast or pixel-level gradients (changes in radiance levels across the image) such as the Sobel index are dependent on haze levels between the observer and landscape features and not just on extinction, and as such were thought to be good candidates to be representative of preference levels.

The same data shown in Figure 4 were plotted against a host of scene- or image-specific metrics including the sky–landscape contrast of the more distant landscape features. As one might expect and reflected by the correlations presented in Table 2, all indexes correlated with acceptability ratings for the WASH and PHX studies, because the images used

were generated with WinHaze, and the only variability in the images is due to haze. Lighting changes from changing sun angle (time of day) and meteorological conditions are constant. However, for the remaining images, the metrics, excluding sky–landscape contrast, are not predictive of acceptability levels. Furthermore, the value of the metric is highly dependent on the scene. The coefficient of variability of metric averages across all six studies for the Sobel index and average contrast is high at greater than 0.3, while for atmospheric extinction and sky–landscape contrast it is 0.12.

The one exception is for the sky–image contrast of the more distant landscape features. Figure 5 shows the acceptability levels for each of the studies, plotted against the apparent contrast of the distant feature that is most sensitive to haze. Also shown in Figure 5 is a logistical model curve fit to each data set. Using the logistic equation fit, the apparent contrast associated with different acceptability percentiles can be estimated, as shown in Table 3.

When the features approximately reach the visual range or a contrast between about -0.03 to -0.05 , about 50% of the observers rated the scene or image as not being acceptable. Referring to Table 1, one sees that these features are about 60–130 km, 42 km, 30 km, 8 km, and 35–100 km for the Denver, Phoenix, British Columbia, Washington, D.C., and Grand Canyon images, respectively.

The Great Gulf study is an outlier relative to the other studies. In this scene the more distant landscape feature had an apparent sky–feature contrast corresponding to the 50% acceptability preference level of about -0.34 , substantially less than -0.03 to -0.05 . This anomaly brings up a context issue. In the Great Gulf study, the participants were only shown images with a limited amount of haze and were required to select images within that range that were unacceptable. Even under the haziest conditions shown, the more distant object was always visible. Therefore, a 50% unacceptability level was chosen where that landscape feature was quite visible. On the other hand, the Grand Canyon image set included images that were unimpaired to totally obscured, while images in the urban studies included many images with enough haze to totally

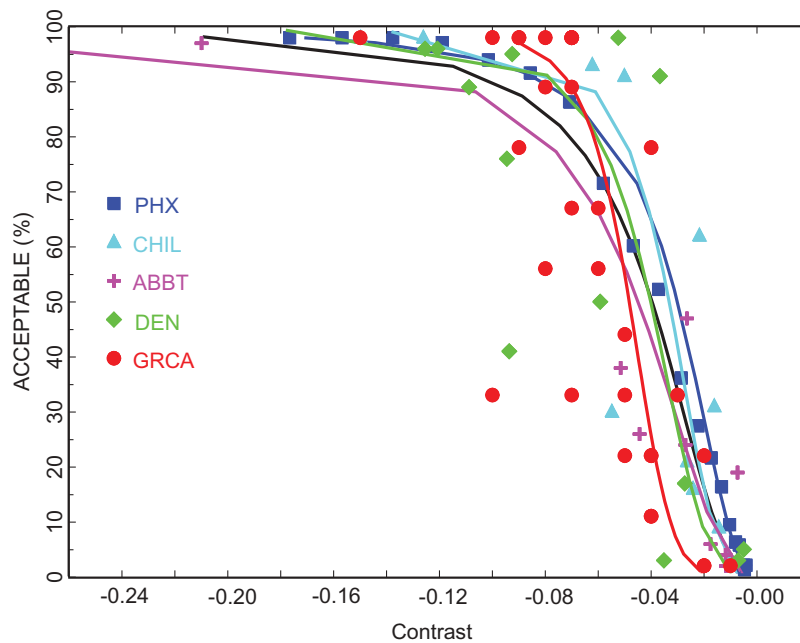


Figure 5. Percent acceptability levels plotted against apparent contrast of distant landscape features.

obscure the more distant features and substantially visually degrade the more foreground urban features.

Robustness of visibility preference studies

Smith (2013) explicitly addressed this type of contextual issue. Smith argued that preference studies, such as those described previously, are not valid measures of an individual's preferences. Smith suggests that preference study results are subject to "framing bias" in that the participants will choose acceptability levels based on the range of visibility conditions to which they are asked to respond. To that end, Smith explored the acceptability ratings of variants of the original Washington, D.C., study described above. The original study, referred to as variant 1, presented 20 different dv levels with five duplicate slides, making a total of 25 slides. The dv levels ranged from a low of 8.8 dv to a high of 38.3 dv. Variant 2 presented only those photographs that corresponded to dv levels of 27.1 and less, resulting in 12 photographs, while in variant 3, two hazier photographs were added that corresponded to dv levels of 42 dv and 45 dv. Three slides corresponding to 24.5 dv, 15.6 dv, and 11.1 dv were removed, as well as five of the duplicate slides used in variant 1. Based on the logit fit, for variant 1 the 50% acceptability level is 28.9 dv, while for variant 2 it is 20.5 dv, and for variant 3 it is 32.0 dv.

It is worth noting that the instructions first had the participants rate the VAQ and then rate the same set of slides as having acceptable or unacceptable visibility

levels. The instructions said, "This time rate the slides according to whether the visibility is acceptable or unacceptable to you." The implicit message was that some of the slides had acceptable visibility while others did not. Therefore, in the variant 2 slide set in which the haziest photo was only at the midpoint, or 50% acceptability point, of the variant 1 slide set, the participants then rated the slide unacceptable, even though in variant 1, 50% of the participants rated it as acceptable.

Even though the variant 3 slide set had the haziest slide increase from 38.3 dv to 45 dv and an increase in extinction of almost a factor of 2, or 100%, the 50th percentile extinction acceptability level only increased by about 33%. Furthermore, the contrast of the most distant feature in variant 1 was about 0.05, while in variant 3 it was about 0.02, consistent with the already-discussed hypothesis that when the more distant features nearly disappear (contrast levels of about 0.02–0.05), the haze level becomes unacceptable to about 50% of the participants.

There are two points to be made. Study participants should be instructed that it is appropriate to find all the slides shown to them to be have either acceptable haze levels, or, conversely, that all slides could be rated as having unacceptable visibility levels. Second, the selection of the slide set should have a range of slides that depict the best to the haziest visibility levels. This could correspond to slides representing Rayleigh conditions to scenes being entirely "hazed out" in which all landscape features are obscured.

Other considerations include the consequences of mixing scenes with varying inherent scenic quality of landscape features, illumination, and meteorological conditions into a single survey on acceptability levels and judgments of VAQ. For instance, mixing images of the same scene under different lighting conditions into the same survey results in those images with less color (shadow) being rated as having lower VAQ than the scene in full sunlight, even though the haze level is identical in both the shadowed and illuminated images. Meteorological conditions can play a similar role, in that scenes with bright cumulus cloud structures tend to be judged as having better VAQ than the same scene without clouds, even though haze levels are the same. To reflect the fact that an observation of a scene is a more or less instantaneous occurrence, preference study designs should only include scenes with similar sun angles or illumination conditions but with varied meteorology. Meteorology can either enhance the scenic quality, as in the case of bright cumulus clouds, or degrade the scene, as occurs with rain or fog events. The next section explores the effect of cumulus clouds on visibility preference or acceptability.

Meteorological factors affecting preference studies

Cloud formations with defined boundaries or edges essentially become integrated scenic features in the observed landscape. Stefani et al. (2012) discuss the positive effect that clouds have on feelings of well-being and subjective tiredness. The Denver, Chilliwack, and Grand

Canyon images were of naturally occurring atmospheric conditions that included cloud formations, while the Phoenix and Washington images were computer generated and did not contain cloud formations. Although the Abbotsford images were taken in a natural setting, they did not contain clouds.

To investigate the role that cumulus clouds might play in haze acceptability studies, Molenaar and Malm (2012) sampled 46 individuals using a protocol similar to those described above. Clouds were synthetically added to the Phoenix and Washington base images using WinHaze, and an image of the St. Louis arch with the downtown urban area shown in the background was added to the survey because it contained a nearby dominant iconic landmark. The cloud structure shown in Figure 6 was the same for all images.

In the St. Louis image, the distance from the observation point and arch is on the order of 1 km, and the structures behind the arch are on the order of 2 km. Figures 6a and 6b show the cloud and no-cloud images under near-Rayleigh conditions (particle-free atmosphere), while Figures 6c and 6d show the corresponding images where 50% of the respondents indicated that visibility levels were unacceptable. The no-cloud image required an atmospheric extinction level of 430 Mm^{-1} ($143 \mu\text{g m}^{-3}$ for a dry aerosol). This should be compared to the extinction levels required for a 50% unacceptability rating for the five urban images previously discussed and shown in Table 3. Of those five urban images, the Washington image required the greatest level of extinction at 192 Mm^{-1} to reach an unacceptability level of 50%,

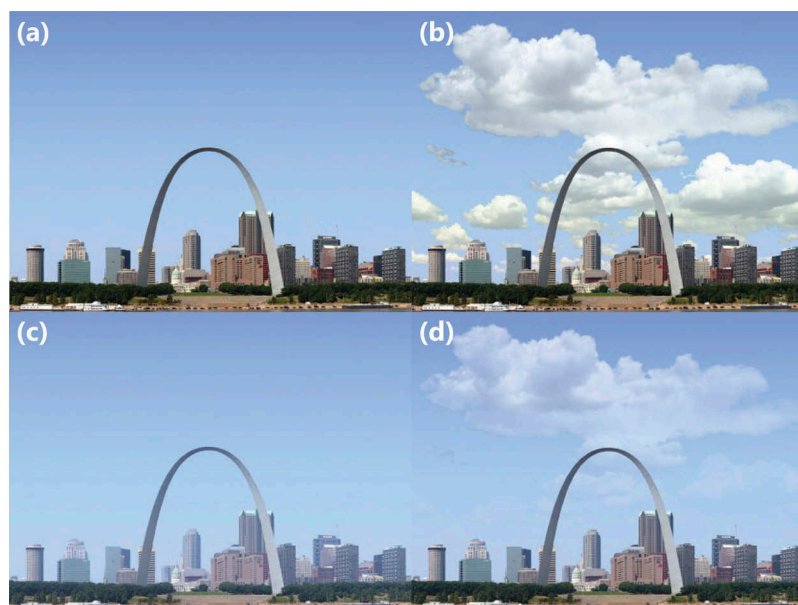


Figure 6. (a) Cloud-free and (b) cloud-added images under near-Rayleigh conditions (particle-free atmosphere). (c, d) Corresponding images where 50% of study participants found the visibility level to be unacceptable.

because the landscape features in that scene were nearer than the other four images. In the case of the St. Louis scene, the landscape features are even closer to the observation point and thus require even a higher level of extinction to reach an unacceptability level.

For the St. Louis image, with clouds added to the scene, the unacceptability level dropped from 430 Mm^{-1} to 236 Mm^{-1} , a drop of about 45%, apparently because at 236 Mm^{-1} the more distant clouds became obscured. For the Washington image, the extinction level for an unacceptability level dropped about 55%. In the case of the Phoenix image, the extinction level for an unacceptability level remained about the same, with or without clouds added to the image. In the Washington and St. Louis scenes, the clouds were the more distant objects, while in the Phoenix scene, the more distant features corresponded to either the mountains or clouds. It seems that landscape sensitivity to haze is highly dependent on meteorological conditions if the meteorological features are more distant than the landscape elements but may have little effect if the landscape features are the more distant elements.

Implications for setting a visibility standard

People living and working in and around urban and natural settings spend time in the work environment, as well as traveling to and from work and various recreational settings. Velarde, Fry, and Tveit (2007) discuss that the inability to see and appreciate landscape features that reflect some sort of natural setting evokes feelings of anxiety and stress-degraded feelings of well-being, resulting in an increased number of sick days and increasing postoperative recovery time.

Visibility in Class I areas, such as national parks and wilderness areas, is already protected by the Regional Haze Rule, which has the goal of bringing visibility back to natural conditions in these areas. However, some consideration should be given to the time people spend in sightseeing activities; going on what might be considered relaxing excursions other than in Class I areas; or just taking a moment to view their surroundings and the sky, be it in from a car, the window of building, or when walking down the street. At any given time, they view landscape and sky features of varying distances. Visibility preference studies suggest that about 50% of individuals would find the visibility unacceptable if at any time the more distant landscape features nearly disappear. This occurs when these features are near the visual range and have contrast levels of approximately -0.02 to -0.05 . An acceptability level of 90% would require that the contrast level not drop below about -0.1 .

To apply these findings in a general way, it is necessary to have knowledge of the spatial distributions of when and where the more distant landscape features, as a function of a population's daily activities, reach some predetermined contrast. If the more distant landscape features nearly disappear or reach a threshold contrast, 50% of the population would judge the scene to be unacceptable. Estimating when a landscape feature reaches a contrast level requires knowledge of the spatial and temporal distribution of the atmospheric extinction coefficient, as well as the distance between the observer and the landscape feature of interest. The governing equation for estimating landscape feature-sky contrast as a function of distance and atmospheric extinction for the i th individual is

$$C_{r_i} = C_0 \exp \left[- \left(\overline{b_{ext}(\vec{r}_i, t)} \right) \vec{r}_i(t) \right] \quad (7)$$

Given a population frequency distribution of C_{r_i} values, a standard or goal could be based on some frequency of occurrence or percentile of the distribution. For example, the C_r value associated with the 90th percentile of the population frequency distribution would have to be below a certain contrast level. For a 50% acceptability level, this contrast level would be -0.05 . Another decision that would have to be addressed is the population size and/or geographic extent for the population frequency distribution.

The above approach would weight the frequency distribution over all time and space equally for all individuals, including time spent indoors staring at a computer screen. An alternative approach would be to develop a frequency distribution of the more distant landscape features in a region to which a population has the potential to be exposed. Some individuals may be routinely exposed to many of the more distant landscape features in a given region, while others may be exposed to them only on weekends, special relaxation trips, or vacation times. The approach discussed above would weight the population distribution of observed distant landscape more toward one individual over another; however, the individual who has the opportunity to see the more distant landscape features less frequently may value the scene as much as or more than the person who has access to them every day.

Distant landscape features include views of iconic structures such as the Empire State Building, viewed while approaching New York City, or views from the top of the Empire State Building of Central Park or the length of Long Island. Many urban areas, such as Chicago, have views down nearby rivers or across large bodies of water. For some areas of the country,

clouds might be the more distant landscape feature that offers feelings of naturalness and well-being.

From a frequency distribution of distances, one could define a characteristic distance, such as the 90th percentile of the distance distribution. Given this distance and a distribution of background extinction levels, a distribution of distant-landscape apparent contrast levels can be derived, and a standard might be set at a level where, for example, 90% of the time a landscape feature at the characteristic distance could be seen.

This framework may also be applicable to rural and even remote areas. The extinction for a 50% acceptability level at Grand Canyon National Park was shown to be 23 Mm^{-1} or $4.3 \mu\text{g m}^{-3}$. This closely corresponds to the estimated natural background $\text{PM}_{2.5}$ level of 1.0–5.0 $\mu\text{g m}^{-3}$, the goal of the Regional Haze Rule.

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