The Perceptual Basis of Vast Space

Roberta L. Klatzky

Carnegie Mellon University

William B. Thompson, Jeanine K. Stefanucci, Devin Gill, and D. Kevin McGee

University of Utah

Correspondence concerning this article should be addressed to Roberta Klatzky, Department of Psychology, Carnegie Mellon University, Pittsburgh, PA 15213. Phone 412-268-8026 email: klatzky@cmu.edu

Abstract

"Vast" is a word often applied to environmental terrain perceived to have large spatial extent. This judgment is made even at viewing distances where traditional metric depth cues are not useful. This paper explores the perceptual basis of vast experience, including reliability and visual precursors. Experiment 1 demonstrated strong agreement in ratings of the spatial extent of 2D scene images by participants in two countries under very different viewing conditions. Image categories labeled "vast" often exemplified scene attributes of ruggedness and openness (Oliva & Torralba, 2001). Experiment 2 quantitatively assessed whether these properties predict vastness. High vastness ratings were associated with highly open, or moderately open but rugged, scenes. Experiment 3 provided evidence, consistent with theory, that metric distance perception does not directly mediate the observed vastness ratings. The question remains as to how people perceive vast space when information about environmental scale is unavailable from metric depth cues or associated scene properties. We consider possible answers, including contribution from strong cues to relative depth.

The Perceptual Basis of Vast Space

Try to recall when you stood in a "vast" space. You might imagine yourself at the Grand Canyon, or staring up at the stars, or perched at the ocean's edge. Although an object like the Colossus of Rhodes or an edifice like the Empire State building may be very large, when "vast" comes to mind it is often in relation to scenes: arrangements of objects and surfaces external to the viewer, generally in natural environments. What vast scenes share is that they extend to very far distances, seemingly without limit. Beyond what appears to be a common phenomenological experience, however, we know little of vastness as a psychological construct; for example, what cues induce it, how reliably they operate, and how it is related to other perceptual variables.

One possibility is that vastness corresponds to an extreme level of perceived depth. If so, the underlying percept cannot specify metric distance, as the traditional cues used to understand metrically scaled depth are uninformative for the very conditions in which spaces are called vast. The effectiveness of most visual depth cues drops off rapidly with distance from the observer, such that beyond 100 meters or so, metric depth estimates are not well supported, if supported at all (Cutting & Vishton, 1995; Loomis & Knapp, 2003). For example, the depth cue of binocular convergence relies on differences in the angles formed by the intersecting lines of sight to a target. Because the magnitude of the intersection angle varies inversely with target distance, angles become more similar as distance increases; as a result, the effective range of the convergence cue is only about 2 meters. Most of the pictorial cues to depth, such as height in the plane or familiar size, also fail to convey vast distances in metric terms. Linear perspective cues do not specify environmental scale unless the viewpoint is known. The cue of occlusion is present whenever objects overlap in the field of view, but offers only a binary cue to

closer/farther. Aerial perspective arises at long distances, but varies unpredictably with moisture and atmospheric contaminants.

Given this limited range of cue utility, estimates of depth in metric terms seem unlikely to account for the sense of vastness that arises from the perception of extensive spaces. An alternative hypothesis is that the sense that a space is vast is a byproduct of mechanisms specialized for scene interpretation. Scene-specific features, such as natural and large, are extracted rapidly (Greene & Oliva, 2009; Joubert et al., 2007), presumably by mechanisms operating at a more abstract level than those giving rise to metric depth (Henderson & Hollingworth, 1999).

The percept of vastness may be related, in particular, to two variables based on the view-specific boundaries that structure the shape around a scene. As initially proposed by Oliva and Torralba (2001), *openness* is inversely related to the number of boundary elements, and *ruggedness* is inversely related to the extent to which contours arise obliquely from the ground plane to obscure the horizon. These variables are not independent, in that extremely open scenes are intrinsically non-rugged, but there are ranges where co-variation is not so constrained. Quantitative estimates of openness and ruggedness were derived for a set of scene images by first subjectively scaling the images according to category (e.g., designating openness as decreasing from coastline scenes to forests; ruggedness decreasing from mountains to fields). Notably, this analysis suggests a relation between these properties and vastness, as mountains and oceans are seen across the large distances associated with vast space. The researchers further showed that openness and ruggedness instantiate specific patterns of spatial frequency, by using a machine algorithm to classify the scaled values from spectral parameters and extracting a best-fit regression with spectral templates as predictors.

The present research constitutes an initial attempt to further our understanding of the perception of vast space and the relation of vastness to known scene properties. Experiment 1, conducted in two countries using different displays, tested whether people could reliably assign subjective magnitudes representing the vastness of 2D photographic images. Variations across scene categories in the magnitude judgments, along with participants' recollection of experiences in vast spaces, suggest that vastness follows categorical distinctions like those used to scale the properties of openness and ruggedness (Oliva & Torralba, 2001). Experiment 2 directly investigated how these variables are related by using separately obtained ratings of openness and ruggedness as predictors of the vastness magnitudes for the same photographs. Experiment 3 assessed the extent to which judgments of metric distance both predict vastness magnitudes and are themselves predicted by openness and ruggedness.

Experiment 1: Subjective ratings of vastness

Method

Participants

Thirty-one (16 female, 15 male) University of Utah college students (mean age = 23 years) participated for course credit in the United States and twenty (10 female, 10 male) Tübingen-area residents (mean age = 28 years) participated for 5 euros compensation in Germany. All participants gave written consent. The sample sizes were based on conventions for standard psychophysical experiments. We targeted 20 participants, but all who were recruited were included in the data, and no analysis preceded the cessation of data collection.

Materials and Apparatus

The stimuli were 134 full-color images of natural outdoor environments, ranging from close views of vegetation to mountains and beaches, which were gathered from pixabay.com and deviantart.com. Examples are shown in in Figure 1.

Fig. 1. Examples of stimulus photographs (originally in color). The leaf and shore images were retrieved from Pixabay. The mountain image was retrieved from DeviantArt, Siegle, Livesey, & Browne (2005), http://creativecommons.org/licenses/by/3.0/, http://austriaangloalliance.deviantart.com/art/Austrian-Peaks-328637716.

In Utah, seated participants viewed the images on an Asus PA246Q monitor, where they subtended a visual angle of approximately 15° wide x 10° high. In Germany, participants viewed the images on a large screen, wide field-of-view projection system from a specified standing point, where they subtended a visual angle of approximately 60° wide x 42° high.

Separately, the pictures were assigned by ten University of Utah students and faculty to one of eight categories of scene content. A reliability analysis found a Finn coefficient (used for categorical ratings; Finn, 1970) of 0.76, $F(\text{inf}, 1179) = 4,17$, $p < .001$. In further analyses, each image was categorized by its consensus assignment, except for eight pictures where no consensus emerged.

Procedure

Participants were told that the experiment investigated cues in a visual scene that might produce the feeling that the depicted space was large. To orient them to the subsequent judgments, they were initially asked to give a description of a time when they felt that they had been in a vast space, including their vantage point. They were told (English version) "a space is vast if it seems to extend without limits away from you, making you feel like a small element within the space." They then transitioned to a rating task, where they were shown a series of images under the instructions, "Using a scale of 0-100, please judge the image in terms of how strongly you feel that the space depicted in the scene feels large." (Large was used in preference to vast, because it is unambiguous in English and has a direct counterpart in German.) Instructions were on-screen in the U.S., oral in Germany. Three images were shown as practice. Participants were told to try to use the full rating scale, while being consistent in how they used it across comparable images. There was no time limit.

Results

Figure 2 shows average ratings for each of the 131 non-practice images for the Germany and U.S. participants. Within-image variability, shown by the standard error, was small relative to the variation in mean ratings across images. Importantly, inter-group agreement was indicated by a strong linear relationship between the two samples, $r(129) = .92, p < .001$, with a slope near unity (1.1). U.S. ratings were larger ($M = 60.05, SD = 10.16$) than German ratings ($M = 50.58, SD = 10.07$), $t(49) = 3.26, p = 0.002$. The essentially constant difference could reflect the viewing angle or posture, but might also reflect cultural variations. Thus, the study indicates that ratings of the largeness of depicted space in 2D images varying in natural content are reliable within and between groups. Although our participants rated largeness of depicted space, we interpret the perceptual dimension that underlies the regularities in their judgments as *vastness*.
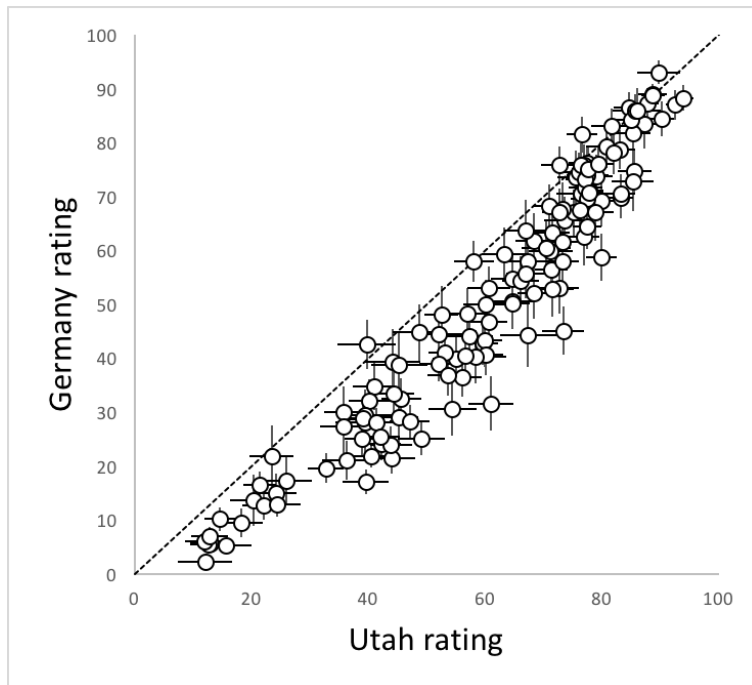
Fig.2. Average rating for German vs. Utah participants by image. Vertical error bars represent

±1 German standard error, horizontal bars represent ±1 Utah standard error. The dashed line

represents complete agreement.

There was clear variation in vastness across scene categories. Detailed analysis is deferred

to Experiment 2, where the variables of openness and ruggedness are considered as well. For

present purposes we note that the categories judged most vast were scenes with a clear horizon

line like an ocean and mountains, and the least vast were forests and close views of vegetation.

These categories also emerged in the analysis of participants' recollections of vast

experience. Their reports (in English except one translated from German) were first submitted to

a lexical frequency count. The most frequent words (at least 10 reports), which tended to emerge

in both countries, were *look, feel, space, vast, large, ocean*, s*mall, see, mountain, and canyon*.

Items with greater than 5 occurrences (N = 26, excluding adverbs and high-frequency verbs)

were submitted to latent semantic analysis (http://lsa.colorado.edu/, data base General Reading

up to 1st year college), which provides a measure of inter-relatedness (cosine between word vectors, range 0 to $\pm$1.0). The high-frequency items having a cosine value with *vast* of .3 or greater were: *large, over, desert, mountain, time, ocean, small, horizon, and valley*. Thus both word count and similarity point to recollected vastness being associated with particular environmental entities and features, most notably those with horizon, height, or depth.

The structure emerging from both vastness ratings and recollected vast experiences echoes the categorical scaling of openness and ruggedness, where highly open stimuli were exemplified by coastlines and highly rugged stimuli by mountains, with forests low on both variables (Oliva and Torralba, 2001). The finding that similar scene categories exemplify high levels on all three variables is consistent with the hypothesis that the sense of vast space may arise from scene-related processing. At the same time, this commonality raises the question of whether the descriptor "vast" adds unique qualities beyond "open" or "rugged." The question of how well vastness can be accounted for by these other scene-specific properties was directly addressed in Experiment 2.

Experiment 2: Relating vastness to scene parameters

Method

Participants

Twenty-two (14 female, 8 male) University of Utah college students (mean age = 26 years) participated for course credit. All gave written consent. Sample size and stopping rule were as in Experiment 1.

Materials and Procedure

The images from Experiment 1 were used in Experiment 2. The participant sat before a Dell U2412M monitor, at a distance such that each image subtended a visual angle of approximately 22° wide by 15° high.

The experimental task was to rate each image on two dimensions derived from computational scene analysis: openness and ruggedness (Oliva & Torralba, 2001). As verbal descriptions of open and rugged can lead to variable interpretations (see, e.g., Kravitz 2011), we asked subjects to assign values to these properties by placing them within an openness/ruggedness space obtained from the original algorithm of Oliva and Torralba (2001). The dimensions were depicted by 64 representative grey-scale images of outdoor scenes, arranged in a 2D openness (x axis) by ruggedness (y axis) grid, as shown in Figure 3(Oliva, unpublished). Under the display conditions, the grid was approximately 19° on each dimension. In addition to the visual depiction of the dimensions, participants were also given verbal definitions: openness was: "not having many obstructions or objects on the ground surface," and ruggedness was: "… protrusions or projections of ground surface into the height dimension, producing an uneven surface."

The 131 images rated in Experiment 1 were presented one at a time, in random order, each placed next to the openness-ruggedness matrix. Participants were asked to point with the mouse to the location that best represented where the current environmental scene fit in terms of the two dimensions (see Figure 3). They clicked to record the location and advance to the next trial. The instructions specified that they were not trying to match to a particular image, but should respond on the basis of the underlying axes.

Prior to making the openness/ruggedness ratings, participants were pre-trained on use of a similar grid, comprising an arrangement of four facial expressions representing variations in

energy (x axis) and *valence* (negative to positive on y axis). They were asked to relate two new

facial images to these dimensions, by using the mouse-click task to be performed in the

experiment proper.

Click on the matrix of images on the right at the position that best represents where it falls along the open and rugged axes.

You can click on any position and are not restricted to clicking in the center of one of the individual images.

Fig. 3. Example trial for rating images as open and rugged. Image on the left retrieved from

Pixabay. Sample and judged images (on left) were in color.

Results

An average openness and ruggedness value was calculated for each image on a 0-1 scale;

the means are shown for the two dimensions in Figure 4 along with the standard error on each

dimension. The variability for openness ($SD = .21$) was somewhat greater than for ruggedness

($SD = .16$). As was noted previously, there is some dependence between these variables (high

openness means low ruggedness) but unconstrained variation is at least possible in some regions

of the scales. The linear correlation between the parameters for this image set was low ($r = 0.01$).

There was, however, a trend toward a curvilinear relationship (for a second-order polynomial fit,

$R^2 = .28$, p < .001), with ruggedness ratings tending to be highest for images that were moderate

in openness. The importance of this relationship emerges in the subsequent analysis.
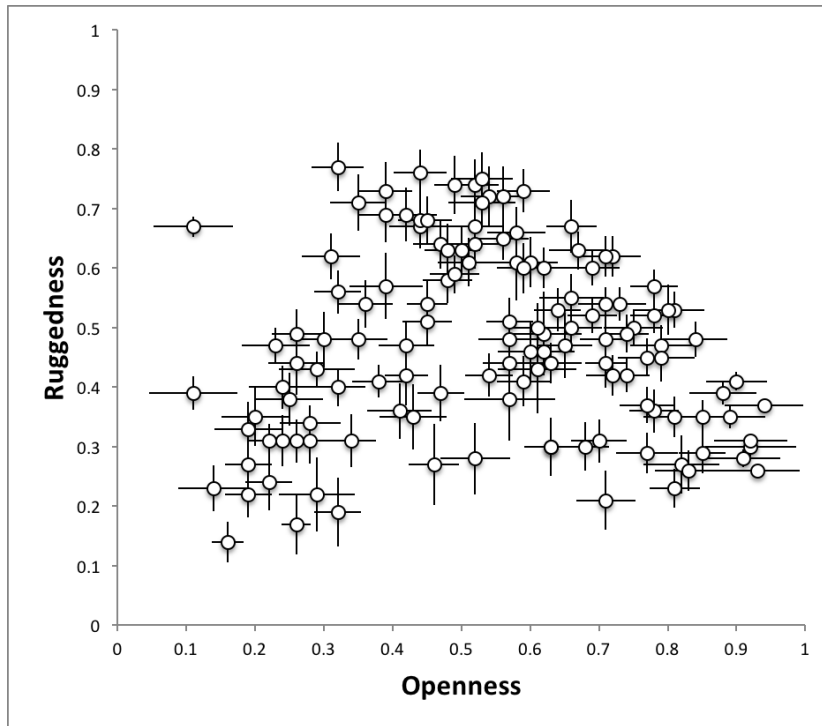
Fig. 4. Average rated ruggedness in relation to openness in Experiment 2, by image. Error bars represent 1 standard error for each dimension.

The principal analysis assessed how vastness, a perceptual response, was related to openness and ruggedness, variables derived from visual properties of scenes. Linear regression using the mean values for each image assessed openness and ruggedness as predictors of the largeness ratings in Experiment 1 (averaged across the two samples). When considered in separate bivariate regressions, both openness and ruggedness were significant predictors of largeness (for openness, β =.78, $p < .001$, R^2 = .60; for ruggedness, β =.46, $p < .001$, R^2 = .21). In an unforced stepwise multivariate regression with greater F-test criterion, openness was entered before ruggedness. As would be expected from the null correlation between the predictors, their coefficients were the same in the stepwise regression as when used in isolation ($ps < .001$). The R^2 increased from .60 in the model with openness as the sole predictor to R^2 = .82 for the

multivariate model, indicating that ruggedness accounted for an additional 22% of the variance

in largeness ratings after openness was controlled, amounting to 55% of the residual variance not

explained by openness.
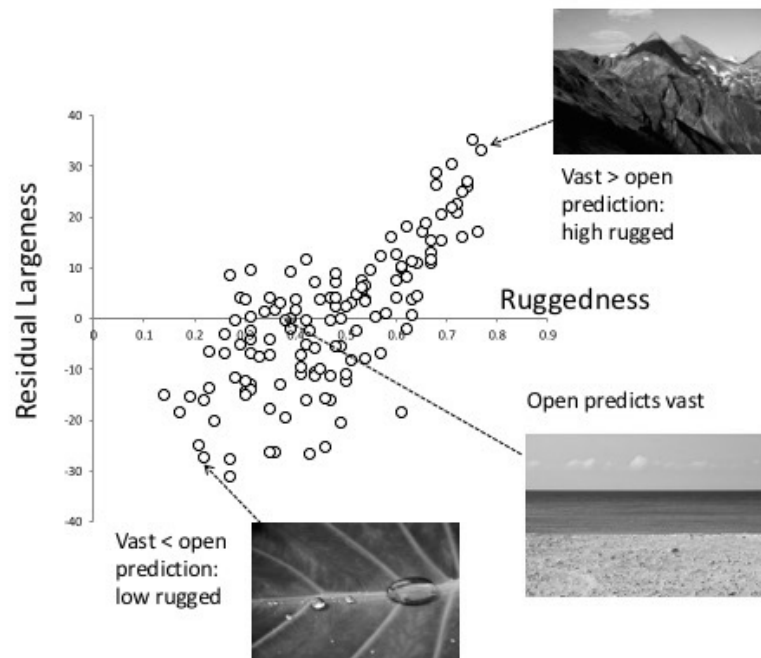
Fig. 5. Residuals after the prediction of largeness by openness, in relation to ruggedness, by

image. Positive residuals indicate that openness under-predicted vastness, and negative residuals

indicate that openness over-predicted vastness. The data points corresponding to the same

scenes as in Figure 1 are shown to illustrate the effects.

The contribution of ruggedness beyond openness can be seen in Figure 5, which displays the

residuals from the bivariate largeness/openness regression against ruggedness and also portrays

examples of specific images for which largeness is predicted vs. over- or under-predicted by

openness. What is apparent is that for those images where vastness was over-predicted by

openness (i.e., where residuals are negative), ruggedness tends to be low. Conversely, where

vastness is under-predicted by openness (i.e., where residuals are positive), ruggedness is high. For images rated at the mean of ruggedness, vastness is well predicted by openness (i.e., the values of residuals are very small).

Experiment 2 demonstrated that ratings of spatial largeness in a depicted scene, which we interpret as perceived vastness, are related to the scene-based categories of openness and ruggedness, which have categorical and spectral signatures. Although at least in our stimulus set, openness was a stronger predictor of perceived vastness, a striking aspect of the results is that the errors made when using openness alone to predict vastness were not random. It appears that images that are not particularly open, but are yet judged to depict vast spaces, tend to be rugged, as in mountain scenes.

A further analysis explored the relation between specific image content and perceived vastness, using the categories identified in Experiment 1. Figure 6 shows the distribution of vastness, openness, and ruggedness by category across the 123 categorizeable images (for all three variables, with vastness rescaled as in Figure 6, *s.d.*s across images in a category ranged from .06 to .14). Vastness and its visual correlates show systematic variations across categories. The category with highest vastness, images with a salient horizon, was also rated most open. However, consistent with the results from the rating task of Experiment 2, openness alone did not predict vastness; mountain scenes, which were rated high in ruggedness but only moderate in openness, were also perceived as vast, and some open categories, such as receding textures, were not vast. The least vast categories were those with low openness and ruggedness.
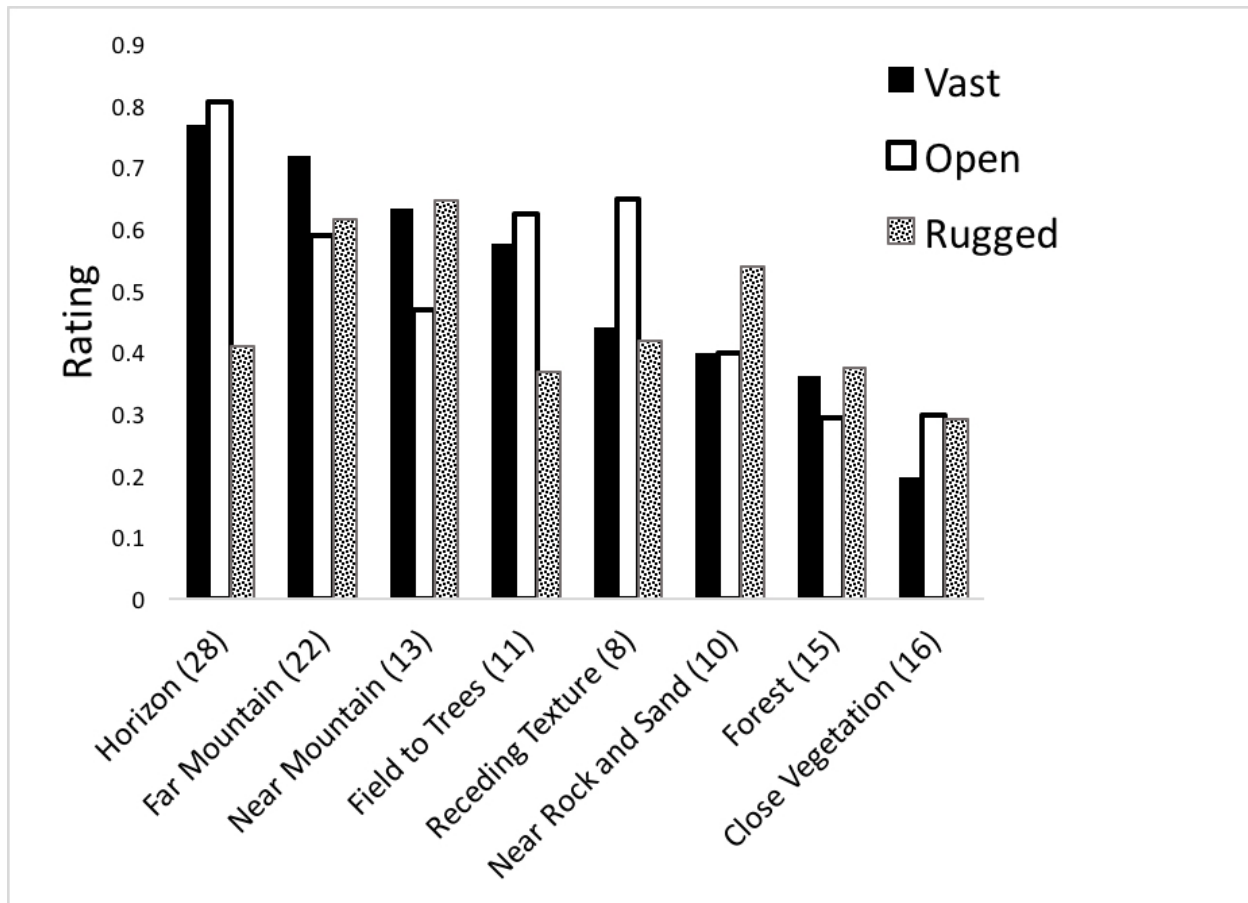
Fig. 6. Mean rating for vastness (divided by 100 to equate scale ranges), openness, and ruggedness, by category. The number of images for each category is shown with the label.

Experiment 3: Relating vastness to metric distance judgments

One would expect vastness to have some relationship to distance in depth, given that vast spaces were defined here in terms of spatial extent. Our approach postulates, however, that the sense of vast space cannot be based directly on knowledge of distance in metric terms, because metric depth cues lack reliability at the scale of spaces considered vast. In a final experiment, we further tested the contribution of distance to vastness by asking people to make judgments of metric depth of the previous image set. Specifically, they judged the distance to the center of the space in a metric of their own choice. This response measure was adapted from Torralba and associates (2002), who obtained metric values (in meters) of "mean depth" of 400 pictured

spaces from observers' judgments. When extrapolated to a larger set of 4000 ranked images,

mean depth was found to be predicted from scale-dependent measures of image structure, which

was taken as support for its use as a measure of metric spatial extent.

Method

The subjects were 29 naïve participants from the same pool as Utah participants in

Experiment 1. One subject was ultimately eliminated, due to deviant responses (individual mean

greater than 5 s.d.s from the overall mean distance). An initial induction, intended to make

participants think of themselves as spatial observers, asked them to "recall an experience of

looking out at a space of near or far objects and surfaces, making you feel like an object at the

edge of the space." They then proceeded to judge the sequence of images used previously, with

the exclusion of one image that depicted only sky. The instructions told participants to think of

themselves as taking the picture and, from what they would see, to report "the distance from the

photographer to the center of the depicted objects and surfaces in the image (not the sky)." They

indicated the distance value and the metric they were using (e.g., yards) for each judgment. All

responses were converted to meters.

Results and Discussion

Two images taken from a viewpoint high above the ground plane produced distance ratings

of > 90,000 meters, more than 3 s.d.s from the mean across images (the corresponding vastness

ratings were 77 and 90). These outliers were eliminated from further quantitative assessment of

distance as a predictor of Utah largeness ratings. The average distance ratings for the remaining

128 images ranged from .06 m to 69,716 m with a mean of 12,130 m.   Largeness was positively

correlated with distance across images ($R^2 = .51$, p < 001). However, as shown in Figure 7, a

power function of largeness vs. distance accounted for considerably more variance ($R^2 = .83$).

Notably, the exponent was 0.13, reflecting a striking compression of largeness across the distance scale. Metric distance and largeness also differed with respect to predictability from ruggedness and openness: A stepwise regression of distance with openness as the sole predictor found $R^2 = .25$, increasing only to $R^2 = .37$ for the model with ruggedness also included. This is well below the $R^2 = .82$ obtained for the corresponding regression of largeness. A further regression addressed whether distance predicted largeness beyond openness and ruggedness. An unforced stepwise regression entered openness first, then ruggedness (i.e., the same model as the previous), and finally distance, which increased the R^2 only by .05.
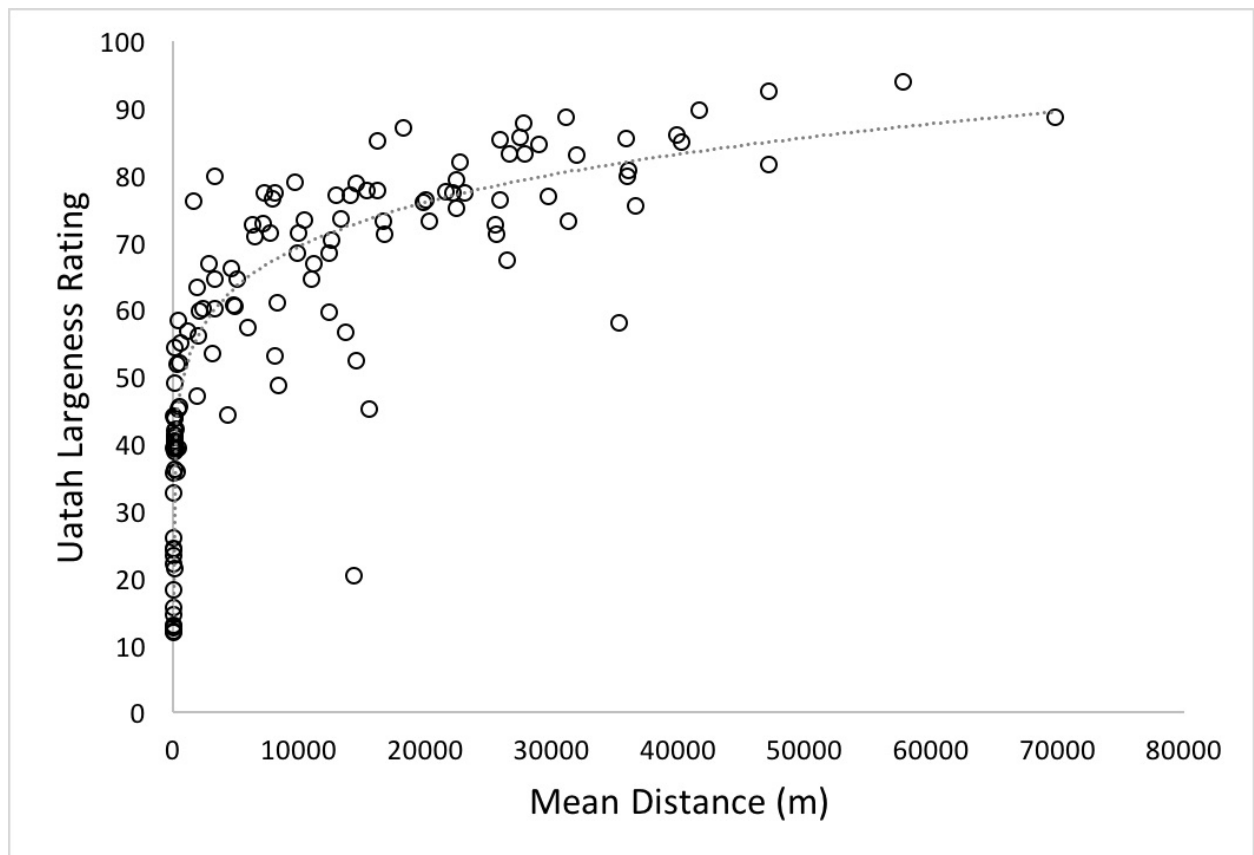
Fig. 7. Average rated largeness by Utah participants in Experiment 1, in relation to average distance judgments in Experiment 3, by image. A power function fit is shown.

Finally, it should be noted that while most participants were able to rate most images sufficiently that the mean distance was significantly correlated with mean largeness, the inter-subject variability was high, as indicated by an average coefficient of variation (s.d. scaled by mean) of 2.4. For reference, the mountain image in Figure 1 had an average rating of approximately 18 miles, but was judged from within a mile to 150 miles away. Moreover, as the s.d. was highly correlated with the mean ($r = .95$), distance judgments were most unreliable for the very spaces perceived to be vast.

The present findings offer little support for the idea that the vastness percept is mediated by an estimate of the distance of visible features and surfaces. If so, substantial inflation at large distance values would be required for the observed mapping of distance into the largeness scale. The further finding that distance, unlike largeness, is not well predicted by openness and ruggedness, together with the obvious difficulty of the metric distance task – not surprising given the paucity of cues – suggest that the perceived extent of surrounding space is not based on processes that yield metric depth perception.

Discussion

The present results indicate that the impression of vast space arising from pictorially presented scenes is a reliable phenomenon. The consistency of ratings of spatial extent point to commonalities in the perception of vastness across individuals within and between cultures, and under varying display conditions. Given that these judgments were based on 2D images of natural scenes, ranging over many orders of magnitude in geometric scale, it appears that people do not have to be physically present or immersively projected into a space in order to judge that it is vast.

Experiment 2 further pointed to geometric and spectral features underlying a sense that an environment is vast. Rated largeness of scenes was robustly related to their openness and ruggedness. Neither of these properties guaranteed a sense of vastness, but the data indicated that natural environments lacking in both will not be evocative of spatial extent. Of the two parameters, openness was a better predictor of perceived spatial extent. Its greater importance is consistent with evidence that cortical areas specialized for scene perception are also sensitive to openness (Kravitz, Peng & Baker, 2011; Park et al., 2011).

These results raise the question of whether vastness identifies some unique aspect of scene perception beyond openness and ruggedness. If the explained variance between German and US ratings ($r^2 = .85$) identifies a target for reliable prediction, the vastness / openness regression ($r^2 = .60$) accounts for 70% of this goal, and openness and ruggedness together account for 96% (multiple $R^2 = .82$). However, describing vastness as a weighted combination of openness and ruggedness overlooks the systematic nature of the prediction, which suggests multiple routes to the vast experience. Spaces described as large can be extremely open, or they can be moderately open but rugged. The linear prediction also fails to account for an essential feature of vastness, the sense that space extends from the viewer without limit.

How this sense of distance is obtained in vast spaces remains an intriguing question. These results indicate that people discriminate degrees of vastness in scenes where much or all of the terrain is viewed at distances where traditional metric depth cues cease to be informative, according to theory and as supported by the findings of Experiment 3. Likewise, openness and ruggedness are parameters that do not in and of themselves provide direct estimates of environmental distance and scale. We speculate that the impression of distance may arise from a combination of relative depth information in the presented scenes (that cannot on its own specify

scale) and further, as yet unspecified, scene properties. For example, an abundance of interposition cues, while failing to support metric distance perception, might allow a scene to perceptually extend in depth essentially without limit. Categorical assignment might also contribute at a semantic level.

Various features of scenes could enhance this experience. One approach, a common compositional convention in nature photography, is to use foreground structures that are within the effective range of standard depth cues and can provide a contrast to the unknowably farther distances associated with a large-scale background. Another influential compositional effect is height in the picture plane (corresponding to angle of gaze in the real world), as in looking up at a mountain from below or looking down on a canyon from above. The contribution of the horizon line to rated vastness could indicate that features arising from perspective structure play an important role in the perception of vastness. Perspective is unlikely to be the whole story, however, since small-scale (i.e., non-vast) environments can also generate strong perspective cues. A limitation of our study is that by using photographs from arts websites, we could not control perspective or enhancements or identify their contributions. Indeed, given that stimulus selection was intended to induce variations in perceived largeness, it seems inevitable that the present vast scenes exemplify conventions meant to enhance the sense of space.

A further possibility is that the perceptual mechanisms involved in vastness are statistical in nature, rather than being salient features or compositional effects. This would be consistent with findings of an association between image statistics and human judgments of scene depth (Torralba & Oliva, 2002 -- although this work did not distinguish between metric distances vs. a more general concept of spatial extent). A statistical approach is supported by the contributions of openness and ruggedness to vastness, as these features have both been shown to be predictable

based on 2-D spectral image statistics (Oliva & Torralba, 2001). Ultimately, the perception of

vastness may be modeled by a multiple-pathway architecture, such as the combination of image

statistics and features, as has been theorized more generally in scene perception (Wolfe et al.,

2011).

To our knowledge, the current experiments are the first to show consistency in the types of

environmental scenes that people rate as vast and to demonstrate that vastness is related to

image-based aspects and conceptual categories of scenes. The importance of these results, we

would argue, goes beyond their perceptual implications and the theoretical questions they raise,

because vastness appears to be something more than a purely perceptual outcome. An expanded

sense of space has been implicated as a precursor to the emotion of awe, which in turn has been

linked to well-being, social engagement and helping behaviors (Rudd, Vohs, & Aaker, 2012;

Van Cappellen & Saroglou, 2012). Alterations of perceived space outside of the body are also

associated with meditative relaxation practice (Berkovich-Ohana et al, 2013).   These tantalizing

connections suggest that a better understanding of the mental state induced by vast environments

could have far-ranging implications.

References

Berkovich-Ohana, A., Dor-Ziderman, Y., Glicksohn, J., & Goldstein, A. (2013). Alterations in the sense of time, space, and body in the mindfulness-trained brain: a neurophenomenologically-guided MEG study. *Frontiers in Psychology*, *4*, 912.

Cutting, J. E. & Vishton, P. M. (1995). Perceiving layout and knowing distances: The interaction, relative potency, and contextual use of different information about depth. In W. Epstein & S. Rogers (Eds.) *Perception of Space and Motion* (pp. 69-117). San Diego, CA: Academic Press.

Finn, R. H. (1970). A note on estimating the reliability of categorical data. *Educational and Psychological Measurement, 30,* 71-76.

Keltner, D., & Haidt, J. (2003). Approaching awe, a moral, spiritual, and aesthetic emotion. *Cognition and Emotion, 17*, 297–314.

Kravitz, D. J., Peng, C. S., & Baker, C. I. (2011). Real-world scene representations in high-level visual cortex: It's the spaces more than the places. *Journal of Neuroscience*, *31*, 7322–7333.

Loomis. J. M., & Knapp, J. M. (2003). Visual perception of egocentric distance in real and virtual environments. In L. J. Hettinger & M. W. Haas (Eds.), *Virtual and Adaptive Environments* (pp. 21-46). Mahwah, NJ: Erlbaum.

Oliva, A. (2013). Scene Perception. In J. S. Werner & L. M. Chalupa (Eds.) *The New Visual Neurosciences* (pp. 725-732). Boston, MA: MIT Press.

Oliva, A., & Torralba, A. (2001). Modeling the shape of the scene: A holistic representation of the spatial envelope. *International Journal of Computer Vision*, *42,* 145–175.

Park, S., Brady, T. F., Greene, M. R., & Oliva, A. (2011). Disentangling scene content from its spatial boundary: Complementary roles for the PPA and LOC in representing real-world

scenes. *Journal of Neuroscience*, *31*, 1333–1340.

Rudd, M., Vohs, K. D., & Aaker, J. (2012). Awe expands people's perception of time, alters

decision making, and enhances well-being. *Psychological Science, 23*, 1130–1136.

Torralba, A., & Oliva, A. (2002). Depth estimation from image structure. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *24,* 1-13.

Van Cappellen, P., & Saroglou, V. (2012). Awe activates religious and spiritual feelings and

behavioral intentions. *Psychology of Religion and Spirituality*, *4*, 223–236.

Wolfe, J. M., Võ, M. L.-H., Evans, K. K., & Greene, M. R. (2011). Visual search in scenes

involves selective and non-selective pathways. *Trends in Cognitive Sciences*, *15,* 77–84.

Acknowledgments