QUANTIFYING EDGE-BLENDED DISPLAY QUALITY: CORRELATION WITH OBSERVER JUDGMENTS

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Abstract

This paper reports the results of a side-by-side evaluation of nine candidate metrics for quantifying edge blend quality in multi channel display systems. The metrics tested include eight variations of contemporary luminance difference and slope-based metrics and a new approach based on a just-noticeable-difference area (JNDA) analysis. The performance of each candidate metric was evaluated by applying each metric to a set of 135 edge blended images which had been degraded using blend zone perturbations typical of those found in multi-channel flight simulators. The pool of degraded images was evaluated by 16 observers who produced ratings of edge blend quality for each image. The performance of each metric was evaluated by calculating the correlation between the metrics and the ratings of quality. The correlation between the JNDA metric and quality ratings was 0.84 and JNDA metric clearly out performed the competing candidate metrics.

Introduction

Multi-channel Flight Simulators

Examination of images in the typical modern multi-channel flight simulator reveals the opportunity for a noticeable improvement in image quality if the projectors could be precisely aligned in the blend regions on a more frequent basis. A review of the adjustments a training center technician must make in order to keep the blend zones in good shape shows that blend zone quality is sensitive to numerous parameters in addition to the "blend zone" controls provided by the projector system. These parameters include the relative spatial shifting of one channel to another, the relative luminance (and color) of adjoining channels, the relative illuminance (shading) across each channel, and the differences in the black levels and gamma functions of the CRTs within the projectors. Discussions with the technicians responsible for keeping these complex display systems aligned makes readily apparent the potential benefit of automating this tedious process.

A significant obstacle in the way of automating the blend zone adjustment task is the lack of a valid metric for measuring blend zone quality. Most projector and display systems specifications acknowledge the need to control edge blend quality in that they attempt to put a specification on it. Often these specifications simply place limits on the maximum luminance difference (e.g., 5%) across the blend zone. While easy to measure using a common hand held luminance meter, this simplistic metric of blend zone quality has the obvious problem that it does not correlate well with the quality judgments of human observers. For example, the visual

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science literature shows that a 1% change in luminance over a visual angle of a few arc minutes is highly visible whereas a significantly larger change (e.g., 10%) can be invisible if the change is made over an angle of many degrees and the change is "smooth."

Candidate Edge Blend Metrics

Prior to this evaluation a number of recent specifications for multi-channel simulator display systems were examined and approximately 15 persons from several companies within the simulation industry were questioned in order to assemble a list of candidate edge blend metrics for testing.

For all of the edge blend metrics identified, the common hand held luminance meter with a 1 deg circular aperture (e.g., Minolta LS-100 or Minolta CS-100) is used. For each of these metrics up to five measurement points are defined. Figure 1 shows the typical locations of these measurement points relative to the blend zone.

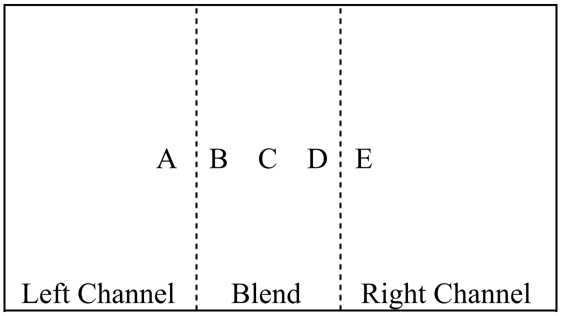

Fig. 1. Measurement Locations for the common metrics of edge blend quality applied to multi-channel simulator displays.

The most commonly specified edge blend metric for moving base flight simulators appears to be the luminance difference metric calculated using three measurement points. With this metric the technician measures luminance at points A, C, and E and then calculates the maximum difference between the three measurements. In this paper this metric is referred to as "**MaxDiff3**."

A simple variation on this metric, identified here as "**MaxDiff3Mean**," uses the maximum difference between each measurement and the mean of the three measurements.

A variation of the three-point difference metric, proposed by a manufacturer of projection displays, uses five measurement points rather than three. A second unique attribute of this metric is that it uses the CIELUV method for calculating color differences (ΔE^*) which allows it to respond to color as well as luminance differences. For this evaluation only luminance differences were introduced into the set of test images, thus, the Δu^* and Δv^* components of the CIELUV-based metric are zero and the metric simplifies to ΔE^* being equal to the maximum difference in luminance among the five measurement points. In this evaluation this metric is referred to as "**MaxDiff5**."

A simple variation on the "MaxDiff5" metric is the "**MaxDiff5Mean**" metric defined here as the maximum difference between the mean of the five measurement points and each measurement point.

Two additional variations on the metrics describe above were included as candidate metrics for testing. These metrics were calculated using the standard deviations rather than the maximum differences of either three or five measurement points and are thus identified as the **StdDev3** and **StdDev5** metrics.

One display system specification for a commercial flight simulator called out an edge blend metric based on luminance slope rather than luminance difference. This specification states the "luminance rate of change shall not exceed 0.15 fL per one deg change of angle." This specification does not define the measurement points but implies that the measurements are to be made in the neighborhood of any "objectionable variations" in luminance.

Two variations of slope-based metrics were included as candidate metrics for this evaluation. For both of these metrics five measurement points were used. The "**MaxSlope**" metric was calculated as the maximum absolute value of slope across the blend zone, whereas the "**StdDevSlope**" metric was calculated as the standard deviation in slope across the blend zone.

Difficulties with existing metrics. From a visual scientist's point of view the most obvious problem with the existing metrics of edge blend quality is the fact that these metrics respond only to the magnitude of luminance changes while largely ignoring the spatial extent over which these changes occur. This attribute of the contemporary metrics flies in the face of the results of dozens of evaluations of human contrast sensitivity which show that the visibility of low contrast stimuli depends heavily on the angular size or "spatial frequency" of the stimuli.

For example, the data of Campbell and Robson (1968), Blakemore and Campbell (1969), Farrell and Booth (1984) and others show that humans have a maximum sensitivity to contrast at a spatial frequency of about 2 to 3 cyc/deg. Their data show that at this frequency contrast can be detected at a modulation of about 0.0025 which corresponds to a contrast ratio of approximately 1.005. What this means is that people can detect a luminance changes as small as 0.5% if that change spans an angular distance of about ¼ deg or less.

On the other hand, these same contrast threshold functions show that a modulation of approximately 0.025 is required to see luminance changes at a spatial frequency of 0.1 cyc/deg. Thus, for luminance changes that span 5 or more deg, a luminance ratio of up to 5% can be invisible if the luminance varies smoothly.

Using a mathematical model for contrast threshold provided by Infante (1991), a modulation of 0.22 is required to see a smoothly varying (cosine) grating at 0.01 cyc/deg at 6 fL which corresponds to the spatial extent of a 50 deg wide image. In other words, a luminance ratio of greater than 1.57 can be invisible if the luminance varies smoothly over an angular distance comparable to the width of a flight simulator channel. This result is entirely consistent with common specifications for relative illuminance which allow the illuminance at the corner of a display channel to fall to as low as 50 or 60% of the illuminance at the center of the channel.

It is clear from evaluations of human contrast sensitivity that allowable contrast varies over large range, depending on the spatial frequency (spatial extent or smoothness) of the luminance transition. For this reason any attempt to quantify edge blend quality that does simultaneously consider contrast and spatial distribution seems doomed to having a poor correlation with quality.

Perhaps the most detrimental aspect of metrics which are uncorrelated with quality are the (unnecessary) arguments that display systems vendors and customers find themselves having over the specifications and measurements. Today it is far too easy to produce a display that is clearly acceptable to the customer but does not pass the specification. Similarly, it is too easy to produce a display that meets the specification but one that even the vendor would not consider to be acceptable.

JNDA Metric

In response to the need for an improved metric of edge blend quality this author has developed the "just noticeable difference area" (JNDA) metric which quantifies uniformity by considering contrast as a function of spatial frequency. Furthermore, this metric contains an explicit model of human contrast sensitivity and uses this data to "perceptually weight" the metric so that it more accurately represents the human observer.

The JNDA metric evaluated here is based on the design of the computational human visual system (HVS) model proposed by Lloyd (1990) which in turn was based largely on the "just noticeable difference" (JND) evaluation approach developed by Carlson and Cohen (1980). The HVS model is patterned after the multi-channel models described by Quick (1974), Wilson and Bergen (1979), and Watson and Robson (1981) which model the overall response of human observers as the responses of a number of independent spatial frequency channels.

Like the "modulation transfer function area" (MTFA) metric of display image quality tested and promoted by Snyder (1985) and his colleagues, the JNDA metric measures the area bounded by the contrast threshold function for human vision and the modulation spectrum produced by the non-uniformity under evaluation. However, the JNDA metric is more similar to the "square root integral" (SQRI) metric promoted by Barten (1987) in that it weights the supra-threshold contrast non-linearly.

The primary difference between the JNDA metric and the MTFA and SQRI metrics is that the latter use as their starting point the modulation transfer function (MTF) which is computed using the Fourier transform of the impulse response (e.g., point or line spread function) of the display system. The JNDA metric does not use the impulse response of the system. Rather, it uses a series of convolutions with octave wide, band-pass, linear (FIR) filters. Because the JNDA metric is not constrained to the impulse response it can be used in a wider variety of situations.

To compute the JNDA metric for blend zones one starts with the "luminance profile" which is a measurement of luminance as a function of distance across the display. The first step in the calculation is to convolve (filter) the luminance profile using a set of band-pass linear spatial filters of the "difference of Gaussians" (DOG) design (Marr, 1980). The DOG filters used have a surround to center size ratio of 1.61 which produces a spatial frequency bandwidth of just over one octave. The magnitudes of the center and surround portions of the filter were scaled such that the filter has a response of zero for DC images and a maximum response of 1.0 when exposed to a linear cosine grating with a modulation of 1.0.

Eight separate linear spatial filters were used in this evaluation and their center frequencies were 4, 2, 1, ½, ¼, 1/8, 1/16, and 1/32 cyc/deg. For each blend zone profile, the maximum response of each spatial filter was found and recorded. For each of these center frequencies the contrast threshold model published by Infante (1991) was used to determine the contrast threshold. Next, each of the eight maximum filter responses was transformed using Equation 1 which scales modulation into number of JNDs.

$$\text{JND} = 61 * [\text{mod}^{0.219} - 1] \qquad \text{(Eq. 1)}$$

Similarly, each of the eight threshold modulations were transformed using Equation 1. For each center frequency the number of JNDs above threshold was determined by subtracting the number of JNDs for the filter responses from the number of JNDs for the contrast thresholds. JNDA was calculated as the sum of the JNDs above threshold for each filter response.

Method

The general method for evaluating the relative performance of the 9 candidate edge blend metrics was to compare the correlation of each metric with a stable set of ratings of edge blend quality obtained using a large group of edge blend conditions containing a variety of blending errors of the type found in multi-channel simulators.

Edge Blend Conditions

For this evaluation a set of 135 edge blend images was produced by using five types of blend zone luminance profile and introducing all combinations of three types of edge blending error including image shift, luminance ratio, and relative illuminance.

Image Shift. Image shift refers to the degree of horizontal spatial misalignment which occurs between adjacent channels. Three image shift conditions were used in the evaluation as indicated in Table 1.

Table 1. Shift conditions.

Condition	Magnitude (deg)	Blend Appearance
1	- 0.125	Light
2	- 0.208	Light
3	+ 0.208	Dark

For conditions 1 and 2 the two channels were pulled towards each other by the amount indicated in Column 2 of Table 1 producing a light bar between the channels. For condition 3 the channels were pulled away from each other producing a dark bar between the channels.

Luminance Ratio. This independent variable refers to the ratio of luminance of the center of one channel relative to the luminance at the center of the adjacent channel. Three levels of Luminance Ratio were used with Conditions 1 to 3 corresponding to one channel being set 2, 12, or 17% brighter than the other. The position of the brighter channel was randomized across the trials and participants: sometimes the brighter channel was on the right, sometimes on the left.

Relative Illuminance (RI). The variable relative illuminance refers to the brightness of the corner of a channel relative to the center of that same channel. Three levels of Relative Illuminance were used in the evaluation with Conditions 1 to 3 corresponding with 50, 65, and 90% RI.

Blend Type. For this variable two separate attributes of the blend zone shape were co-varied, luminance profile and width, as shown in Table 2.

Table 2. Blend Zone Types.

Condition	Luminance Profile	Blend Zone Width (deg)
1	Linear	4
2	Linear	6.5
3	Cos^2	3
4	Cos^2	4
5	Cos^2	5.5

Blended Image Examples

The effects of each of the independent variables on the luminance produced on the display system are illustrated in Figures 2-4 by graphically showing the resulting display luminance for a few selected examples. The caption of each figure lists the settings for each of the experimental variables.

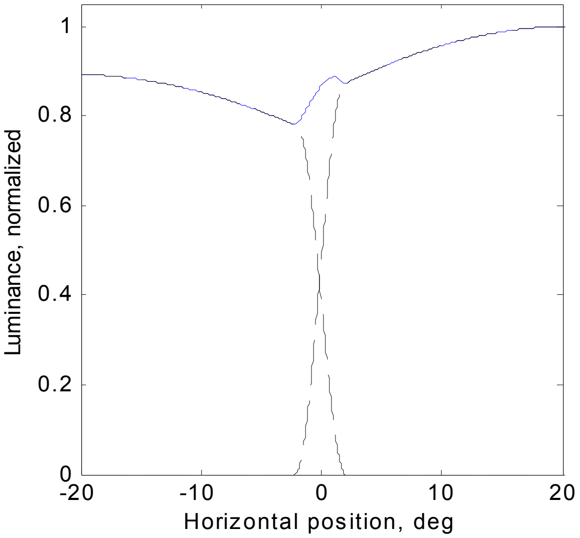

Fig. 2. Luminance across the channels for a 4 deg wide $\cos^2$ blend zone profile. For this condition the channels were shifted together 0.208 deg, the right channel was 12% brighter than the left, and the relative illuminance was set to 65%.

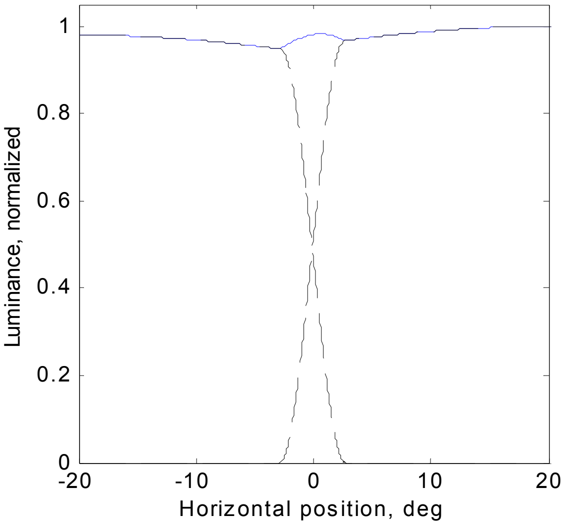

Fig. 3. Luminance across the channels for a 5.5 deg wide $\cos^2$ blend zone profile. For this condition the channels were shifted together 0.125 deg, the right channel was 2% brighter than the left, and the relative illuminance was set to 90%. This condition represents the best case used in the evaluation.

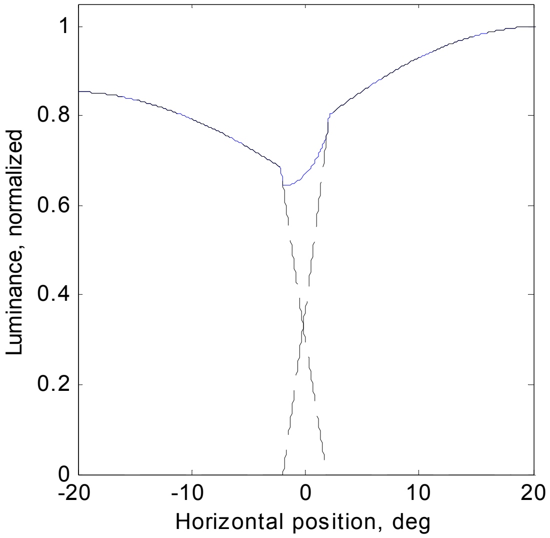

Fig. 4. Luminance across the channels for a 4 deg wide linear blend zone profile. For this condition the channels were shifted apart 0.208 deg, the right channel was 17% brighter than the left, and the relative illuminance was set to 50%. This condition represents the worst case used in the evaluation.

Participants

As originally planed a total of 8 participants were to provide ratings of edge blend quality for this evaluation. The analysis of the data from the first few participants seemed to indicate a systematic difference in the responses between participants experienced and non-experienced with edge blend adjustments. For this reason the number of participants was doubled so that this supposed difference could be analyzed. Once the data were collected from all 16 participants, the statistical analysis revealed no reliable difference between the experienced and non-experienced groups.

The ages of the sixteen participants ranged from 24 to 61 with a mean age of 39.6 years. Thirteen of the participants were male and three were female. Nine of the participants were rated at med-hi to high experience while seven were rates as having little to no experience with edge blend adjustments. All of the participants worked for BARCO Xenia and were not paid extra for their participation in the evaluation. None of the participants were informed of the specific goals of the evaluation prior to their participation.

Display

Images were presented on a calibrated 21 in (nominal) direct-view CRT monitor, set to display 1024 x 1280 pixels in true color mode at a 75 Hz refresh rate. The active area of the screen used to display the blend zone patterns used 900 x 1260 pixels and measured 26.4 x 39.6 cm (10.4 x 15.6 in) for a sampling rate of 32 pix/cm (81 pix/in). The observers eye point was set level with the center of the screen and the eye-to-screen distance was set at one screen width +/- about 2 cm. The eye-screen distance was monitored during the evaluation and the participant was asked to re-position if they drifted too far from the desired distance. At this viewing distance the display subtended 53 deg in width and 37 deg in height. Figure 5 shows the relationship between the observer and the display.

Figure 5. Photograph of a participant seated with an eye-screen distance of one screen width. The horizontal bar in the image is an artifact of the photographic process and was not visible to the participants. The faint, dark, vertical bar down the center of the image is the simulated blend zone.

The mean luminance of the display was held at 51 cd/m^2 (15 fL). The lighting in the room was adjusted so that the mean wall luminance within the observers field of view was less than twice the display luminance. Just prior to data collection the gamma curve of the display was measured using a Minonta LS-100 photometer. The display was measured in the experimental environment, thus, the gamma correction curve accounted for reflected ambient illumination as well as the luminance produced by the display. A gamma correction function was generated and applied to the image data in order to linearize the display. Additionally, the spatial distribution of luminance was measured for the display and a spatial correction function was applied to the data. Both the gamma curve and spatial distribution of luminance were re-measured after data collection and were found to have remained stable.

The images were pre-filtered to attenuate the highest spatial frequencies so that potential aliasing artifacts could be eliminated and the video amplifier of the display could more easily (and accurately) reproduce desired luminance profiles. In angular terms the Nyquist sampling limit of the display was 24 cyc/deg, thus, the response of the low pass pre-filter was set to pass 50% at 12 cyc/deg.

Procedure and Instructions

Upon arrival at the experimental site the experimenter read written instructions to each participant to familiarize them with the experimental procedure and equipment. Participants were instructed to provide ratings of the "quality of blended flight simulator images" which were presented on the CRT. Ratings of quality were to be made using a rating scale ranging from 1 to 10 where a 10 was to be assigned to conditions where the blend zone was completely invisible. If the non-uniformity was barely visible but not at all objectionable participants were instructed to use a rating of 9. Non-uniformities that were more visible were to be assigned lower numbers and the participants were instructed not to assign ratings below one.

Participants were instructed that many attributes of the image would change from trial to trial including the blend zone width, shape of the blend zone, peak luminance of one channel relative to the other, sharpness of the brightness transition, and relative illuminance within each channel. The participants were instructed to assume that the person who adjusted the two projectors was supposed to have accurately adjusted the edge blend controls, shading, black level, peak white, and geometry. The goal of the participant was to rate the "overall quality of the final blended image."

Prior to the regular data collection session a series of 15 practice trials were presented to familiarize each participant with the procedure and the range of blend zone qualities to expect during the regular trials. On each trial the blend zone was presented for approximately 10 seconds after which the participant verbalized their rating for the experimenter to record. The series of regular trials required approximately 40 minutes to complete for each participant. Each participant viewed the 135 test images in a different random order to cancel out any systematic effects of practice or fatigue.

Data Reduction

As is typically found with rating scale data, individual participants use the rating scale differently with some persons using a small range of ratings (e.g., 4 to 7) and others using a much larger range (e.g., 2 to 10). If the data from all participants were simply averaged together, the data from those participants who used a large range of ratings would influence the overall pattern of results more strongly than the data of participants who used a small range. Thus, prior to computing the average ratings across the participants the variance of the data from each participant was normalized so that the standard deviation of the scores from each participant was equal to the mean standard deviation for the group of 16 participants. This normalization was done without changing the mean of the ratings from any one participant.

After normalizing the variance and averaging across participants the mean ratings ranged from a low of 3.50 to a high of 8.87. No statistically reliable differences in the ratings were found between the experienced and non-experienced groups of participants, thus, the results presented below apply to the entire group of 16 participants.

Results

Ratings of Edge Blend Quality

Figures 6 to 9 show the mean ratings for each of the four independent variables (averaged across the remaining variables) used in the evaluation. For these figures the average standard error of the mean (SEM) was 0.17 rating scale points, thus, the 95% confidence intervals span a range of +/- 0.33 points. Most of the differences between the means plotted in the figures are statistically reliable with the exceptions noted in the text.

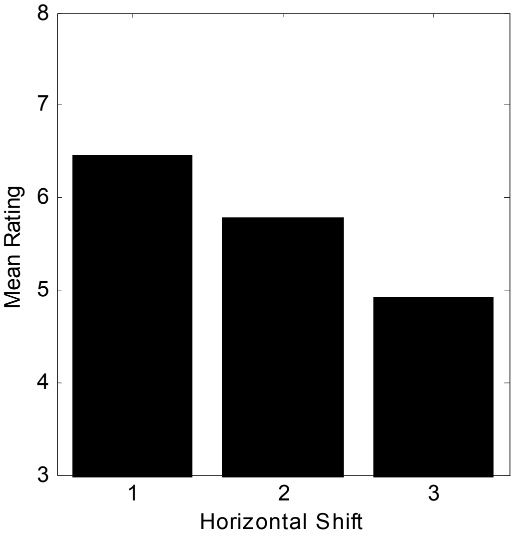

Fig. 6. Effect of horizontal shift error between channels on mean ratings of edge blend quality. Condition 1: 0.125 deg together, Condition 2: 0.208 deg together, Condition 3: 0.208 deg apart.

Comparing the ratings for Conditions 1 and 2 shows that the 0.208 deg shift error (together) produced lower ratings than the 0.125 deg shift error (together) as would be expected. Comparison of the ratings for Conditions 2 and 3 reveals a more interesting finding in that a large difference in ratings is produced using horizontal shift errors of the same magnitude. These data suggest that pushing the channels together, which produces a bright bar between channels, is better than pulling the channels apart by the same amount, which produces a dark bar between channels.

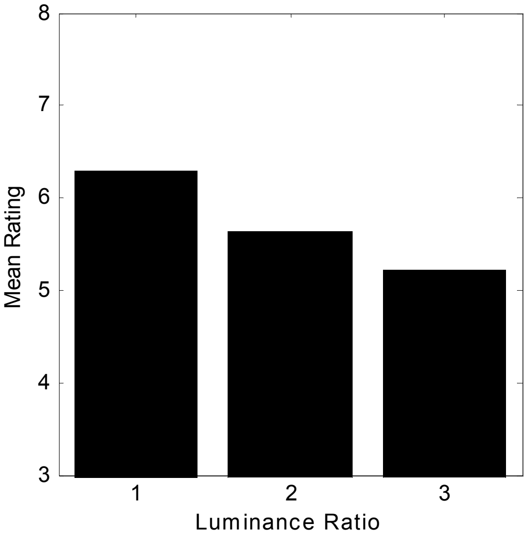

Fig. 7. Effect of luminance ratio (one channel relative to the other) on mean ratings of edge blend quality. Conditions 1 to 3 were 2%, 12%, and 17% respectively.

Examination of the data in Figure 7 reveals the reduction in the rating is linearly related to the luminance ratio (R^2 = .996). Given this relationship a luminance ratio of 1 would be expected to produce a rating of 6.44.

As indicated in Figure 8 changing the relative illuminance from 65 to 50% reduced ratings significantly, whereas there was no difference in ratings between the 90 and 65% conditions. Unlike the highly linear effect of luminance ratio these data suggest the effect of relative illuminance is strongly non-linear. Reducing RI to 65% apparently has no effect whereas ratings fall off sharply somewhere between 50 and 65%.

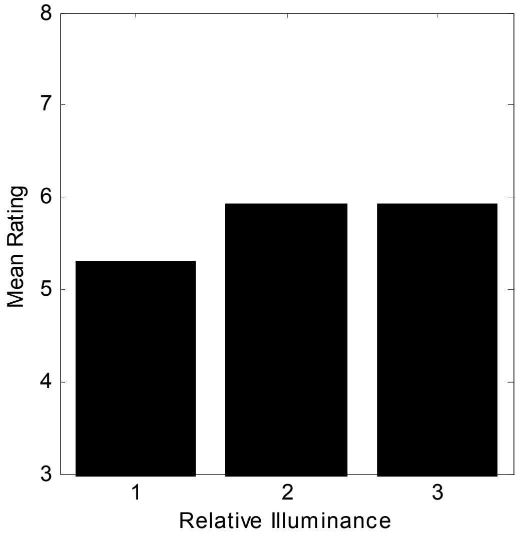

Fig. 8. Effect of relative illuminance (center to corner of each channel) on mean ratings of edge blend quality. Conditions 1 to 3 were 50%, 65%, and 90% respectively.

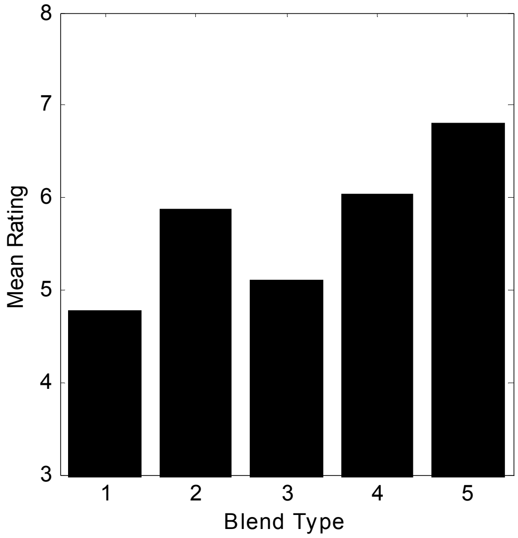

Fig. 9. Effect of blend type on mean ratings of edge blend quality. Linear luminance profiles with blend zone widths of 4 and 6.5 deg were used for Conditions 1 and 2. Cosine^2 profiles with blend zone widths of 3, 4, and 5.5 deg were used for Conditions 3 to 5.

Examination of the mean ratings in Figure 9 shows that for both the linear and the cos^2 blend zones, ratings increase as the blend zone width increases. Comparison of Conditions 1 and 4 shows that for blend zones of the same width (4 deg) ratings were notably higher for the cos^2 profile as compared with the linear profile.

Best Possible Metric

Suppose it were possible to formulate a blend zone metric that measured perfectly the same physical attributes of the display that the human observers responded to. One might expect that the correlation between the "perfect" metric and the ratings scale data would be 1.0, however, this is not correct because of the unavoidable variance in the rating scale data. Prior to evaluating the performance of the practical metrics described above, it is instructive to know how well the "best possible" blend zone metric would perform.

For the rating scale data collected in this evaluation the SEM averaged 0.40 for each of the 135 experimental conditions. At this level of within and between-subject variance the highest possible correlation any metric can achieve was calculated to be 0.947.

Relative Performance of Metrics

Column two of Table 3 lists the correlation coefficients obtained for each of the 9 candidate edge blend metrics. The R^2 correlation coefficient can be interpreted as quantifying the proportion of the variance in the quality ratings that is "explained" by the metric. If the coefficient is zero, then the metric has no ability to predict quality and is useless as a metric. If the coefficient were 1 then the metric would perfectly predict quality. Column three of the table shows the percentage of the variance that is not explained by the model, thus, it quantifies the degree of randomness in the metric.

Table 3. Correlation of each metric with ratings of edge blend quality.

Metric	Correlation R^2	% Variance Remaining
MaxDiff3	0.309	69
MaxDiff5	0.345	66
MaxDiff3mean	0.316	68
MaxDiff5Mean	0.327	67
StdDev3	0.316	68
StdDev5	0.308	69
MaxSlope	0.385	61
StdSlope	0.304	70
JNDA	**0.844**	**16**
Best Possible	0.947	5

Note: Column 3 provides the percentage of variance that is not explained by the metric.

Examination of the data in the table reveals that the JNDA metric is a much better predictor of blend zone quality than any of the eight variations on contemporary metrics. The variance left unaccounted for by the JNDA metric is only 26% of that of the closest runner up. The second best performing metric was the MaxSlope metric which explained 38.5% of the variance in the rating scale data. However, examination of the coefficients for the eight variations on the contemporary metrics reveals little practical difference in their performance.

Discussion and Conclusions

Of the nine blend zone metrics tested, the JNDA metric is the only metric that was explicitly designed to be responsive to the spatial distribution of luminance in addition to contrast. Additionally, the JNDA metric is the only metric that is "perceptually weighted" meaning it explicitly accounts for the visual performance of the human observer. The high percentage of variance explained by the metric indicates the metric is responsive to those attributes of blended images that are relevant to human observers.

The contemporary metrics of blend zone quality can all be measured rapidly using a common hand held luminance meter. It seems that these metrics were "designed" on the basis of convenience. Unfortunately, the testing reported here indicates these metrics explain only a small percentage of the variance. However convenient, these metrics do not measure relevant attributes of blended images.

While the measurement and computation of the JNDA metric is clearly more complex than the contemporary metrics, this process can be completely automated. Given the capabilities of modern CCD camera systems, which can be readily calibrated in the intensity and spatial domains, we no longer need to constrain the metrics used to specify and evaluate complex multi-channel display systems to what is convenient using a hand-held luminance meter.

Future Research

In this evaluation the computation of the JNDA metric was made using one-dimensional luminance data measured perpendicular to the blend zone. In the dissertation work of Lloyd (1990) two-dimensional spatial filters were employed demonstrating that the JNDA approach is readily extensible to the measurement of uniformity in two dimensions. Thus, it is expected that this approach will be applicable to the general problem of uniformity measurement and can be used for the automated adjustment of two dimensional projector parameters such as shading and relative illuminance.

The HVS model developed by Lloyd (1990) contained spatial-*chromatic* channels responsive to red-green and blue-yellow differences as a function of spatial frequency. Thus, it is expected that the JNDA method will be applicable to the measurement of color as well as luminance uniformity.

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