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EFFECTS OF SPATIAL LUMINANCE NONUNIFORMITIES ON VISUAL-TASK PERFORMANCE AND SUBJECTIVE UNIFORMITY

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Effects of spatial luminance nonuniformities on visual-task performance and subjective uniformity

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The objectives of the experiment described in the paper were the determination of the effects of nonuniformities on operator performance and perception, and the validation of current recommended standards. Subjects performed two tasks in the presence of nonuniformities: an objective visual search task, and a subjective magnitude-estimation task for the determination of perceived uniformity. The results indicated that the nonuniformities did not appreciably affect search performance, and that current recommendations are appropriate, although the magnitude-estimation task results indicated that the subjects were sensitive to the nonuniformities. The subjective impressions of perceived uniformity results follow the contrast threshold function of the visual system.

Keywords: display luminance nonuniformity, perceived uniformity, visual displays

In visual displays, systematic changes in luminance or colour are used to present image details and grey-scale rendition. The term *display-luminance uniformity* refers to the ability of a display to present a uniform luminance across the display screen, and this is important for the appearance of a continuous picture. The term *display nonuniformity* refers to unintended changes in luminance or colour on the display that may result in image degradation. From a marketing standpoint, displays that manifest obvious nonuniformities may be aesthetically displeasing to the customer. From a performance standpoint, nonuniformities may directly affect task performance.

Research that investigates the effects of display nonuniformities has been very limited. McCann, Savoy, Hall and Scarpetti[1] investigated continuous linear luminance gradients and sinusoidal periodic patterns. If a 50% detection likelihood is defined as the threshold, a constant of 0.12–0.17 was required for the dimmest edge of a linear gradient to be identified. A contrast of 0.33 resulted in detection rates of 93%.

McCann *et al.* also presented subjects with sinusoidal luminance gratings at a constant contrast of 0.10. The results were similar to those of other experiments dealing with sinusoidal gratings. As the spatial frequency increased, the visibility increased monotonically. At 2.8 cycle/deg, the subjects responded correctly 100% of the time. At the lowest spatial frequency (0.5 cycle/deg), correct responses were at chance levels.

Limited research can be found on high-frequency luminance gradients or changes in luminance or colour at the elemental or pixel level. Such nonuniformities may include blemishes, dirt on the screen, or a change in luminance of the pixel. (This definition does not include the luminance change with respect to the element size.) The acceptable level also varies with the number of nonuniformities on the screen.

Emissive displays may exhibit luminance variations in pixels such that the luminance is below or above the intended level. Matrix or cell-addressed displays may

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fail by having a pixel remain on or off irrespective of the intended state. The effects of display failures have been investigated, and the results indicate that, as random cell failures increase from 0% to 20% of the active display area, reading and random visual-search performances decrease. In addition, it has been found that display failures are more detrimental when a random search task is performed than when a reading task is performed. With a 4% failure rate, the search performance is degraded by 28%, and the reading performance is degraded by 4%, from a no-failure condition. For search-type tasks, ON cell failures (cells that match the character luminance) above 1% should be avoided[2–4].

The research described above revealed that display failures that cause high-frequency nonuniformities across the screen influence performance; however, acceptable levels and quantitative predictive metrics for describing high-frequency nonuniformities are difficult to establish. In prior studies, the spatial frequency of the nonuniformity was not varied, and nor was the degree of luminance change (or amplitude of the nonuniformity). Further research is still needed.

Without an accurate and standard definition of the term *nonuniformity*, it is difficult to describe and measure the effects on performance. Farrell and Booth[5] categorized cathode-ray tube (CRT) nonuniformities into systematic and nonsystematic changes in screen luminance. Two examples of systematic nonuniformities are phosphor burn and the luminance difference from the centre to the edge of a CRT screen. Examples of nonsystematic nonuniformities were described as blemishes, for example dynamic and static blemishes caused by the writing or erasing of functions. Blemishes can be either lighter or darker than the background luminance.

It is not feasible to list and describe all of the different types of nonuniformities that may exist in each of the different display technologies. Goede[6] proposed the categorization of nonuniformities into three types, as follows.

- *Large area:* luminance or colour gradients from one area on the screen to another, such as edge-to-edge or centre-to-centre gradients. An example is the centre-to-edge luminance difference commonly found on CRTs. Because CRTs have curved screens, the beam strikes the phosphor at oblique angles, which is the primary cause of the luminance difference.
- *Small area:* luminance or colour changes from element to element. Examples of this type of nonuniformity are blemishes, dirt specks and element failures.
- *Edge discontinuity:* luminance or colour gradients that extend across a boundary, resulting in the impressions of edges or discontinuous figures. For example, some flat-panel displays are manufactured such that several small displays are matrixed together to form one large-screen display. The boundaries where these smaller displays are joined may result in impressions of edges. Another example is the line failures that are common to some displays.

While these categories are somewhat useful, they are limited. The definitions of 'large' or 'small' areas are not adequately specified. The extent and type of luminance gradient are also not defined. The nonuniformities discussed above refer to luminance or colour changes that are inherent in the display technology. Another example of nonuniformities is Moiré patterns, which may appear with the introduction of mesh glare filters placed over the display. Also, a digitized image may result in nonuniform outputs, because of the sampling rate used. These types of nonuniformities do not fall neatly into the above categories.

The American National Standard for human-factors engineering of visual-display-terminal workstations[7] provides a recommendation for acceptable levels of nonuniformities. The standard recommends that the luminance variation from the centre to the edge of the active display area should vary by no more than 50% of that of the centre luminance. In reference to high-frequency spatial luminance nonuniformities, the standard requires that unintended luminance variations shall not vary by more than 50% within an area the size of half a degree of arc, at any position on the screen. (This value is calculated on the basis of the display design viewing distance.) This last recommendation ensures that, if a 50% luminance change does occur, it does not occur sharply, creating the impression of an edge or dark spot.

Research objectives

It is obvious that empirical research that describes the effects of spatial luminance nonuniformities on human performance is lacking. Validation of current recommendations is needed. Electronic displays are used for many critical tasks, such as photointerpretation, sophisticated cartographic and symbolic representation for many military systems, computer-aided design and computer-aided manufacturing (CAD/CAM), and other graphics applications. The display of an accurate continuous image may often be critical to task performance. Although operators may be able to perform such tasks with displays that exhibit nonuniformities, it is not known how the nonuniformities may affect performance. It is possible that the effects of luminance nonuniformity may vary with the type of task and the type of information displayed. The objectives of the research described in this paper are the definition of nonuniformities in a manner that allows systematic measurement, the determination of the effects of nonuniformities on visual-task performance and perception, and the validation of current recommendations.

METHOD

Underlying this investigation is the concept of the visual system as a Fourier analyser in the spatial domain. The techniques of linear systems analysis and Fourier analysis are powerful analytical tools that can provide a quantitative measurement framework for the description of nonuniformities. Also, a large body of literature in the areas of vision and visual display systems uses a spatial-frequency model for the description of human visual responses. Description of nonuniformities in spatial frequencies allows the comparison of results with previous research.

Visual detection thresholds vary as a function of spatial frequency, modulation, and the shape of the gradient (e.g. sine wave versus square wave). Therefore, nonuniformities were defined in terms of spatial frequency, which allows nonuniformity to be described as a continuous variable, the discrete arbitrary definitions of large and small area thus being avoided.

In addition to the above variables, visual detection thresholds have also been found to vary as a function of the display luminance[8]. Because display luminance is a parameter that display users may adjust, it is important to include this variable in the investigation. For example, older users, or observers who are viewing under high-glare conditions, may increase the display luminance. Nonuniformities may vary in two dimensions on the screen; therefore, the effects of 1D and 2D nonuniformities are also included in the investigation.

The description of nonuniformities in terms of spatial frequency, modulation, and gradient shape permitted the systematic physical measurement of the nonuniformities with the use of photometric techniques. Physical measures of the nonuniformities were then correlated with human visual performance.

Experimental design

The experimental design was a 7 × 6 × 3 × 3 × 2 complete factorial, and it is shown in Figure 1. Seven levels of spatial frequency (FREQ) were evaluated: 4, 8, 16, 32, 64, 128 and 256 cycles per display width (cycle/DW). The 256 cycle/DW condition consisted of waveforms of 2 pixels on and 2 pixels off. The waveform generators were bandwidth-limited beyond this spatial frequency. The lower frequency value of 4 cycle/DW was selected on the basis of research by Hoekstra, van der Goot, van den Brink and Bilsen[9], who found that, when the spatial frequency was held constant, the number of cycles presented in the grating affected the

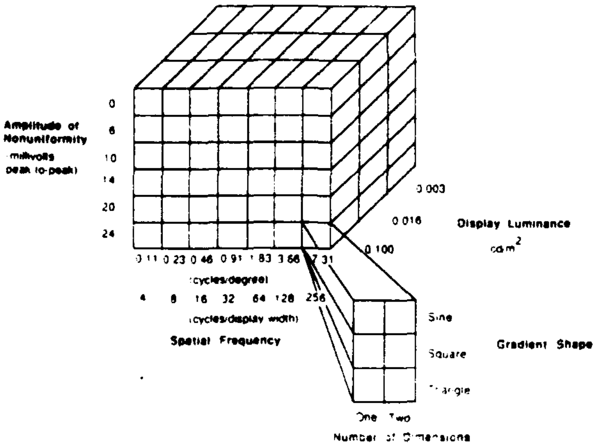

Figure 1. Experimental design

threshold modulations. The critical number of cycles varied as a function of luminance. For the range of mean display-luminance values of interest in this study, the critical number of cycles was approximately 4. Figure 1 also includes the frequency values in units of cycles per degree of visual angle (cycle/deg) at the fixed viewing distance of 45.7cm.

The six levels of amplitude (AMP) in the peak-to-peak voltage were 0, 6, 10, 14, 20 and 24 mV. The AMP-0 condition was included as a baseline condition. That is, nonuniformities were absent. The three levels of display luminance (DL) were DL-1 = 0.003, DL-2 = 0.016, and DL-3 = 0.100 candelas per square metre (cd/m^2). The term *display luminance* refers to the mean luminance of the nonuniformity, and it may also be considered as a luminance DC offset. Three gradient (GRA) shapes were investigated: square (SQ), triangular (TRI), and sine (SINE). The variable dimension (DIM) included 1D and 2D nonuniformities. The 1D nonuniformities were in the vertical direction only; that is, the pattern was vertically oriented. The 2D condition consisted of horizontal and vertical nonuniformities summed together.

Subjects

45 students from the Virginia Polytechnic Institute and State University, USA, served as subjects and they were paid \$5.00/h for their participation. 15 subjects participated in the random search task, and 30 subjects participated in the magnitude-estimation task. All the subjects were between the ages of 18 and 30 years old, and the mean age was 20.5 years. Each subject was screened for normal or corrected 20/22 near and distant vision, and normal lateral and vertical phoria, with a Bausch & Lomb Orthorater. Each subject was also screened for normal near and far contrast sensitivity with a contrast-sensitivity test by Vistech Consultants Inc., USA.

Apparatus

The imaging system consisted of a 48.3cm diagonal monochrome cathode-ray tube, a video-signal generator, two programmable function generators, a custom-built horizontal-line generator (HLG), and an IBM-PC AT computer.

The CRT monitor was a high-resolution Tektronix GMA-201. The monitor was driven at 60Hz in non-interlaced mode, and it had an addressability of 1024 × 1024 pixels within an active area of 27.94 × 27.94cm. The CRT had a standard P4 phosphor, and it was interfaced with an OPIX video-signal generator produced by Quantum Data. The OPIX was capable of a 200MHz pixel rate with a nominal rise/fall time of 1.8ns.

Two programmable function generators (Tektronix 5010) produced the nonuniformities. The generators controlled the amplitudes, display luminances and frequencies of the nonuniformities. One function generator was used to produce the vertical nonuniformities, and the other was used to produce the horizontal nonuniformities. Each generator was capable of a frequency range of 0.002–20.000 MHz, and output amplitudes of 0.02–20.00 V peak to peak. The generators were triggered and synchronized by the OPIX, and they had a frequency stability of 0.10%.

The function generators were not phase locked to the OPIX or the display. When a square wave from the horizontal-function generator was presented, the horizontal lines on the display flickered on and off. Therefore, a custom-built horizontal-line generator was used to generate the square-wave shapes for the horizontal signal. The HLG was capable of controlling the FREQ, AMP and DL values, and the values were set to match the output of the vertical- and horizontal-function generators. The HLG was controlled manually, and it was only used for the SQ 2D nonuniformities.

The IBM-PC AT was used as a terminal to control the OPIX and the programmable function generators. The function generators and the OPIX were interfaced to the IBM-PC AT with the General Purpose Interface Bus (GPIB) communications system. A Microsoft mouse was used as an input device, and it was connected to the IBM-PC AT.

Stimuli

The nonuniformity patterns were created with the function generators. The FREQ, AMP, GRA and DL parameters were sent to the function generators via the GPIB system from the IBM-PC AT. These nonuniformities were presented in two task situations: a random search task and a magnitude-estimation task.

During the random search task, map patterns and symbols were generated by the OPIX video-signal generator. 26 US Army symbols were constructed in an 11 × 15 matrix. The 11 × 15 matrix subtended 19 × 26 arcminutes of visual angle. Numbers were used as identification tags for the symbols, and they were created in the upper-case 11 × 15 Lincoln/MITRE font. The map patterns were generated by an algorithm that drew lines on the display in a pseudorandom fashion. The lines were 1 pixel wide. The symbols and maps were presented at a level of 65 bit, which corresponded to a luminance level of approximately 4.13 cd/m^2. Note, however, that the symbol luminance was added to the DL levels, and so the symbol- and map-luminance values were actually higher. When the nonuniformities were also added, the luminance of the symbols increased more when the symbol fell on the light portion of a cycle than when it fell on a dark portion of a cycle. The modulations of the symbols and maps varied for each DL level. For the 1D conditions, the luminance modulations were approximately 0.998, 0.992 and 0.951 for DL-1, DL-2 and DL-3, respectively. For the 2D conditions, the modulations were approximately 0.989, 0.992 and 0.849 for DL-1, DL-2 and DL-3.

During the magnitude-estimation task, the map and symbol information was not displayed; only the nonuniformity patterns were presented.

Human-performance tasks and procedures

Random search task

A noncontextual random search was used in which the dependent measure was search time. This task was chosen because research has shown that observers are able to perform contextual-type tasks, such as reading tasks, under adverse conditions (see Reference 10). Lloyd *et al.*[4] found that the random search task was more sensitive to high-frequency display-failure nonuniformities than was a reading task. For the random search task, the gradient variable was assigned as a between-subjects variable, and all the other variables were within-subjects variables, resulting in 252 conditions for each GRA. Each condition was repeated five times for a total of 1260 data points per subject. Five subjects were randomly assigned to each GRA level.

At the beginning of each trial, a prompt was displayed on the screen that stated 'Ready, the next target is . . .', with the search target displayed. When the subjects were ready to begin searching, they pressed the button on the mouse input device, and the map, 26 symbols and nonuniformities were displayed. All the symbols were randomly placed on the screen. The symbols and the map lines never overlapped. After locating the target, the subjects pressed the mouse button, and the nonuniformity and the symbols were removed. A symbol identification (ID) number was displayed in the area to the right of each symbol position. The subjects reported the symbol ID that corresponded to the target symbol that they had found. The ID number was randomly selected for each symbol during each trial, so that subjects could not memorize a specific ID number in association with a specific symbol. The subject responses were input to the computer by the experimenter. The responses were timed from the onset of the first button press to the second button press, with the IBM-PC clock function being used. The clock had a resolution of ±55 ms. There were five trials per condition, resulting in 1260 trials per subject. All the trials were presented in random order

Magnitude-estimation task

Although subjects might be capable of performing an objective task in the presence of nonuniformities, it is possible that nonuniformities might be aesthetically displeasing. The magnitude-estimation task was included to determine subjective impressions of the nonuniformities. The magnitude-estimation task required subjects to provide a magnitude rating of the perceived uniformity; that is, subjects rated how uniform the luminance appeared to them. Note that the subjects were told to rate perceived uniformity rather than nonuniformity, because nonuniformity cannot be defined without biasing responses. However, subjects could, and did, understand the term 'uniformity'. Higher numerical values indicated that the subjects perceived the display as appearing more uniform. The rating was the dependent variable. For this task, the variable DIM was treated as a between-subjects variable, and all the others were treated as within-subjects variables, resulting in 378 conditions for each DIM.

Each condition was repeated twice for a total of 756 data points per subject. 15 subjects were randomly assigned to each DIM condition.

At the beginning of each trial, a 'ready' prompt was displayed. When the subjects were ready to give their perceived uniformity ratings, they pushed the button on the mouse input device, and a nonuniformity pattern was displayed. The subjects were given as much time as they needed to report their ratings. The ratings of perceived uniformity were input to the computer by the experimenter. All the trials were presented randomly.

RESULTS

Random search task

For each subject, the mean of the five trials per condition was calculated and used in subsequent analyses. Analysis-of-variance (ANOVA) procedures were then performed on the dependent-variables search time over the five trials per condition, with the Statistical Analysis System (SAS, Version 5.18) being used on an IBM 3090. *Post hoc* simple-effect F tests were performed to evaluate significant interactions, and the Newman–Keul comparisons test was performed to compare means.

The results of the analysis indicated that one 3rd-order effect (DL × GRA × DIM) and the main effect of the DL variable were statistically significant ($p<0.05$). The effects of the DL will be discussed in terms of the interactions. Figure 2 shows the DL × GRA × DIM interaction ($F(4,24)=3.21$, $p=0.0303$). For both the 1D and 2D conditions, the search times were faster for SINE waves than for TRI or SQ waves. Also, as the DL variable increased, the search time, in general, decreased. A simple-effect F test indicated a significant interaction between DIM and DL for the SQ-wave condition. For the 2D SQ wave, there appeared to be little difference between the three DL levels, although there was a slight increase in the search time from 0.016 to 0.100cd/m^2. For the 1D case, the search time decreased as DL increased. The SQ wave, the highest level of DL for the 2D condition, did not decrease the search time, probably because the nonuniformity pattern was beginning to interfere with performance, reducing the benefit of higher DL levels.

The results of the analysis indicated that the effect of nonuniformities on the search time is negligible. The subjects were able to perform the task with little effect on search-time performance. Only two effects appeared to be consistent. An interaction between GRA, DL and DIM indicated that the SQ and TRI waves were more degrading to the search time than the SINE wave. A possible explanation may be that, because the modulations of the SQ- and TRI-wave fundamentals are higher than those of the SINE-wave fundamental; thus, they are more distracting to subjects. A contributing factor is probably the visible 'edges' of these waveforms at lower spatial frequencies. The effect of DL was also consistent.

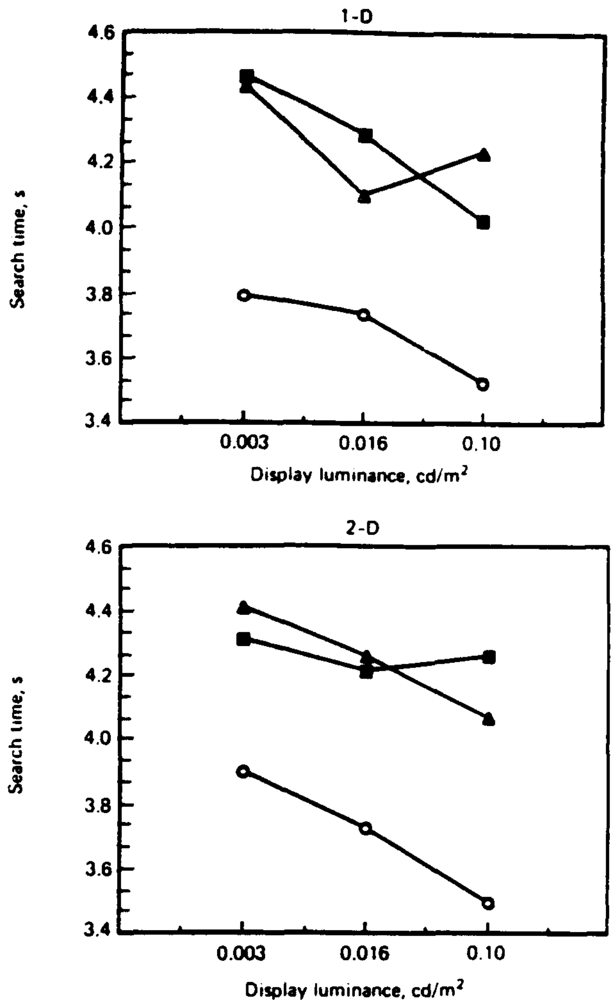

Figure 2. DL × GRA × DIM interaction for search time [○: SINE, ▲: TRI, ■: SQ.]

The lack of performance differences may be explained by several factors. First, the luminances of the nonuniformities were added to the symbol luminances; therefore, the symbol/background modulations were always above the recommended (e.g. ANSI 1988) levels. That is, the nonuniformities did not degrade the symbol modulation. Also, the nonuniformities were systematic, and they had the appearance of a background to the map and symbols. Perhaps the subjects were able to ignore the nonuniformities. If the nonuniformities had been random, it might have been more difficult to separate visually the nonuniformities from the symbols.

Another possible explanation is that the nonuniformities, which can be considered as noise, were always at spatial frequencies that were below the spatial frequency of the targets and maps that were composed of 1 pixel-wide lines; therefore, masking effects did not occur.

Although the subjects were able to perform the search task in the presence of nonuniformities, many subjects commented that the nonuniformities were annoying and fatiguing. Some subjects also commented that the SINE-wave shapes were blurry. Long-term performance with a display that exhibits the nonuniformity levels used in this study might induce eye fatigue and strain over many hours.

Magnitude-estimation task

For this task, the free-modulus technique was used. The free-modulus technique allows subjects to select their own scale to describe the stimuli presented. The data are then transformed to place ratings of perceived uniformity on the same scale. The data were transformed with the use of the method described by Engen[11]. Before scaling, a constant of 101 was added to each rating of perceived uniformity for all subjects to bring the range into the positive domain. The range of the subject mean perceived uniformity scores was 11–301. These values were used in the analyses.

After scaling, two separate analysis-of-variance procedures were performed. One analysis included the AMP-0 condition, which was a baseline; that is, nonuniformities were not presented (other than those inherent in the display itself). The baseline was an important variable that gave an indication of how different from a uniform screen the subjects estimated the nonuniformities to be. It also served as a check on the reliability of the subjects' perceptions. The subjects would be expected to rate the AMP-0 condition as being the same throughout the study. In addition, an analysis without the baseline was included, because it was often difficult to determine whether significant effects were being unduly weighted by this AMP-0 condition. Table 1 lists the significant effects for both the ANOVA procedures. The trends remained the same with the removal of the baseline.

Many of the effects of the magnitude-estimation task are statistically significant and meaningful. Although the subjects' random-search performance was not detrimentally influenced by nonuniformities, the subjects were sensitive to the nonuniformities. The definition of nonuniformities in terms of FREQ, AMP, DL, GRA and DIM was successful, and the effects on the perception of uniformity caused by each variable are discussed below.

Table 1. Comparison of significant effects for ANOVAs with and without AMP-0 baseline

Source of variance	Baseline included F	Baseline included p	Baseline removed F	Baseline removed p
FREQ	20.65	< 0.0001	19.16	< 0.0001
AMP	23.78	< 0.0001	13.19	< 0.0001
DL	23.68	< 0.0001	23.03	< 0.0001
GRA	11.42	< 0.0001	10.82	< 0.0001
FREQ*DL	7.60	< 0.0001	7.51	< 0.0001
FREQ*AMP	17.07	< 0.0001	5.66	< 0.0001
FREQ*GRA	7.72	< 0.0001	7.30	< 0.0001
AMP*DL	17.76	< 0.0001	1.80	0.0777
AMP*GRA	7.44	< 0.0001	0.81	0.5932
DL*GRA	6.30	< 0.0001	5.65	0.0004
FREQ*AMP*DL	21.40	< 0.0001	0.86	< 0.8006
FREQ*AMP*DIM	0.80	0.7632	2.62	< 0.0001
FREQ*GRA*DIM	1.71	0.0624	1.73	0.0591
FREQ*AMP*GRA	3.33	< 0.0001	1.77	0.0011
FREQ*GRA*DL	1.75	0.0153	1.64	0.0289
FREQ*AMP*DL*DIM	1.45	0.0151	1.60	0.0063

Display luminance

Display luminance is an influential variable, and it interacted with many of the other variables. In general, as DL increased, the perceived uniformity decreased (when nonuniformities were present). When nonuniformities were absent (the baseline condition), the subjects rated a luminance of 0.10 cd/m² as being more uniform than the lower DL levels, which might be a function of the instructions, which stated that the subjects were to rate how uniform in 'luminance' the screen appeared. The subjects might have been looking for luminance, although they were instructed not to rate the screen on the basis of how 'bright' it appeared.

DL interacted with FREQ as shown in Figure 3. The effects of DL were stronger at middle FREQ levels, and these results resemble the contrast threshold function (CTF) of the visual system at its lower frequencies. Also, the effect of DL was greater for SQ nonuniformities than for SINE or TRI nonuniformities. This effect is also consistent with previous research in spatial vision, which shows that lower modulations are required to detect SQ waves (see Reference 12).

Amplitude

As AMP increased, the perceived uniformity decreased (it appeared to be more nonuniform), and the effect of AMP interacted with FREQ, as shown in Figure 4. As FREQ increased, the effect that AMP had on perceived uniformity decreased. Again, these results can be explained by models of spatial vision. As FREQ increases, the modulations of the waveform harmonics do not reach visual threshold detection levels, and therefore do not contribute to detectability. At 4, 8 and 16 cycle/DW, the fundamental and third, fifth and seventh harmonics (for the SQ and TRI waves) had modulations above detection thresholds. At 32 cycle/DW, the seventh harmonic was no longer detectable for many of the AMP levels. At 64 cycle/DW, the fifth harmonic was undetectable. At 128 cycle/DW, the detection of the third harmonic was limited. At 256 cycle/DW, the modulation passed by the display for the fundamental frequency was 88% of the modulation passed at 4 cycle/DW, and all the harmonics were undetectable. These results verify previous research that investigated the CTF of the visual system to SQ waveforms.

Gradient

Figure 5 shows the interaction between FREQ and GRA. The subjects consistently rated the TRI and SINE waves the same, even though the TRI wave had harmonics that were visible at the lower FREQ levels. *Post hoc* analysis indicated that the use of the SQ wave resulted in significantly lower ratings of perceived uniformity than the use of the SINE and TRI waves. Also, the harmonics of the SQ wave were more visible (i.e. they had higher

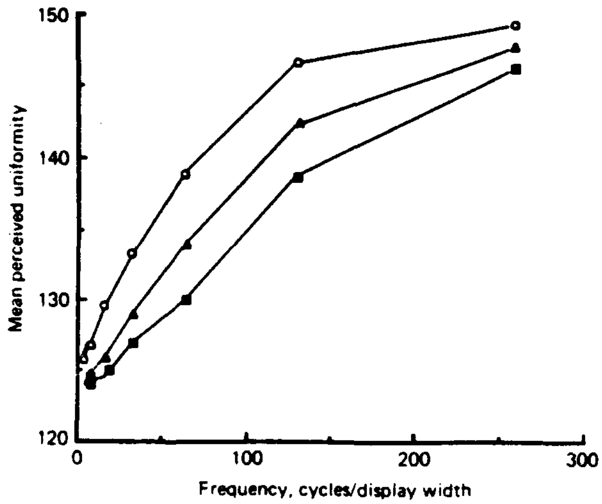

Figure 3. FREQ × DL interaction for perceived uniformity
[○: DL = 0.003, ▲: DL = 0.016, ■: DL = 0.100]

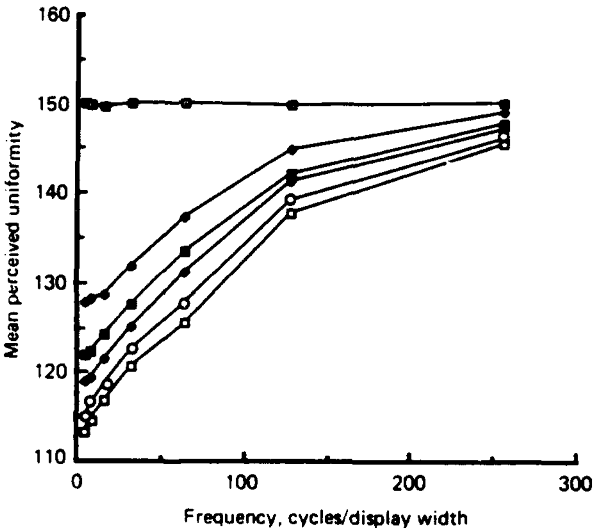

Figure 4. FREQ × AMP interaction for perceived uniformity
[■: A-0, ◆: A-1, ■: A-2, ◆: A-3, ○: A-4, □: A-5]

modulations) than the harmonics of the TRI wave. For certain combinations of FREQ, AMP and DL, the harmonics of the TRI wave were not visible, while the harmonics of the SQ wave were. As FREQ increased, the harmonics of the SQ wave did not reach threshold detection levels, as discussed above. At 128 cycle/DW and 256 cycle/DW, the subjects could not tell the difference between GRA shapes at their viewing distance (45.7cm). The effect of the SQ shape decreased as the harmonics became undetectable. The results also verify previous research that investigated the CTF of the visual system for SQ waveforms.

Dimension

The effect of DIM is difficult to interpret. The FREQ × AMP × DIM interaction was significant (F (24,672) =

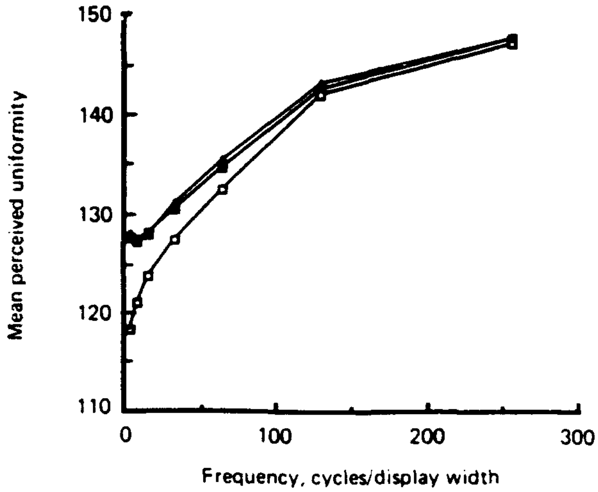

Figure 5. FREQ × GRA interaction for perceived uniformity
[■: SINE, ▲: TRI, □: SQ]

2.62, $p < 0.0001$) only when the baseline (AMP-0) was removed from the analysis. However, during the course of the experiment, it was noted that a confound existed between DL and DIM. It is obvious that DL is an influential variable; therefore, it is not unlikely that DL played a prominent role in the effect of DIM. Additional research is necessary to determine the difference between 1D and 2D nonuniformities. If DIM strongly influenced perceptions, DIM would probably have interacted significantly with more variables.

DISCUSSION AND CONCLUSIONS

Human performance and current standards

The results of the research described in this paper indicate that very noticeable spatial luminance nonuniformities do not appreciably affect performance for search-type tasks. The nonuniformities in this study exceeded the recommendations of the ANSI standard[7], and the search performance was relatively unaffected. The ANSI standard is written for displays that are to be used for alphanumeric or word-processing and reading type tasks. The research in this paper indicates that recommendations are also appropriate for search tasks with nonalphanumeric symbols. Results of this type will most likely be applicable to reading-type tasks, because it has been found that subjects are able to perform reading tasks or contextual tasks under adverse conditions[4,10].

Although the subjects were able to perform the random search task in the presence of nonuniformities, the results from the magnitude-estimation task indicated that the subjects were sensitive to nonuniformities in terms of their impressions of the perceived uniformity. Sensitivity to the nonuniformities was noted during the random search task. While performing the search task, many subjects complained about the images, and found them annoying. Some subjects commented that the SINE waveforms appeared blurry, and that performing the task was fatiguing. Focusing on the SINE wave was difficult, because there were no edges.

Most displays currently on the market do not inherently exhibit the levels of nonuniformity used in this study. However, nonuniformities may be caused by components or processes of a display system other than the display hardware. Possible causes of nonuniformities that may result in high levels of nonuniformities include signal-processing techniques that are necessary for the transformation of signals so that they can be displayed or enhanced, or coding techniques, such as spatial dithering or halftoning.

Relationship with previous research

As pointed out at the beginning of this paper, research that investigates the effects of nonuniformities is limited. Abramson and Snyder[2], Decker *et al.*[3] and Lloyd *et al.*[4] investigated the effects of display failures that could be considered as high-frequency nonuniformities. Cell and line failures were caused on the display, and the results indicated that these types of nonuniformity were degrading to both search and reading performance. The high-frequency nonuniformities in the study described in this paper were not detrimental to search performance. A possible explanation for the difference in results is that, in the previous research, the failures introduced onto the display were random, while the nonuniformities in the authors' study were not. In fact, the nonuniformities had the appearance of being a background to the task information, rather than an interruption in the image, and the subjects were apparently able to ignore the nonuniformities. The 'hard failures, on the other hand, degraded the information by removing parts of the images or adding extra cells or lines, resulting in the appearance of visual noise.

The nonuniformities used in the study were additive. When the display luminance was increased, the symbol luminance increased. Therefore, the modulations of the symbols and maps remained above recommended levels of modulation (e.g. the ANSI standard[7]). Failures degrade the image, and change the modulation of symbols or characters as well. The introduction of nonuniformities that are not additive will probably result in further degradation of the image, and performance will deteriorate.

Spatial vision

The results of this investigation strongly concur with previous research in the area of spatial vision, which theorizes that the visual system behaves as a Fourier analyser in the spatial domain. De Palma and Lowry[12] found that threshold detection is lower for a square wave than for a sine wave. The amplitude of the fundamental frequency of the square wave is $4/\pi$, 1.273 times higher than that of the sine wave, and the harmonic frequencies of the square wave contribute to detection. Thus, in consistency with prior research, Fourier techniques and the spatial-frequency approach can be applied successfully to describe the nonuniformities, and to predict perceptual performance, as they have also been successfully applied to other research in the area of visual displays[13].

The results of the perceived uniformity data follow the CTF of the visual system. In many cases, previous researchers have only reported results that used one or two well trained subjects. The research described in this paper, which used a much larger subject population, validates previous research in terms of the CTF.

Future research needs

Research that investigates the effects of nonuniformities is still needed. The role of 1D, as opposed to 2D, nonuniformities was not adequately assessed. Also, the nonuniformities in this study were added to the symbol luminances; therefore, the symbol modulations were always well above recommended levels. Nonuniformities will not always be additive, and the effects of nonuniformities that change the information presented should be investigated.

The description of nonuniformities in terms of spatial frequencies allows for systematic measurement. The next phase of this research is that of photometrically measuring nonuniformities, and using the information to develop predictions of human performance. If the same techniques as are used in this study are also used to define and measure nonuniformities in future studies, prediction across studies will be possible.

It is recommended that research be conducted that investigates the effects of nonuniformities on performance with other tasks. If the performance of objective tasks can be correlated with subjective-task performance, information relating to subjective performance can be used in the design processes. Objective-performance data are often more expensive to obtain than subjective data. Prediction across different types of task would also be beneficial to the design of visual display systems. The type of task performed is an important consideration. Tasks that require the extraction of information from a literal image where grey scale is used to present picture details (for example in a digitized picture) may be more sensitive to nonuniformities. In these tasks, the nonuniformities may not appear to be a background, but an interruption in the continuity of the image. Research that correlates the performance of different tasks and predicts results across task types is also lacking. Photointerpretation tasks, or information extraction from literal images, such as medical imagery, will be the most likely to show different results.

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