Correspondence

Multidimensional Scaling of Multiply-Impaired Television Pictures

J. S. GOODMAN AND D. E. PEARSON

Abstract—**The application of multidimensional scaling analysis to similarity judgments made between pairs of impaired television pictures containing combinations of four basic signal impairments (quantizing distortion from a differential pulse code modulator, echo, random noise, and bandwidth limitation in the form of low-pass filtering) is reported. The analysis revealed four dimensions used by observers which were interpreted as: 1) overall picture clarity, 2) a distinction between impairments which form an overlay pattern on the picture and those which distort objects in the picture, 3) the amount of stationary overlay patterning, and 4) the amount of moving overlay patterning. The overall picture clarity dimension was the most important in terms of observers' rated preference for the variously impaired television pictures. Interaction between the impairments was complex but readily interpretable in terms of the revealed dimensionality.**

INTRODUCTION

In the transmission of television signals over communication channels, several different kinds of impairments arise. Of particular interest is the way in which these impairments combine subjectively [1]–[4]. Pictures with several different physical distortions simultaneously present are said to be *multiply impaired*; with such pictures (and also with some singly impaired pictures) the visual distortion introduced can be complex, and it is not always clear what cues or dimensions feature in observers' judgments or whether physically independent impairments are perceived as psychologically independent. The study reported in this paper sought to throw light on these aspects, with the ultimate aim of improving our understanding of the link between physical and subjective magnitudes of impairment in television systems.

We report, in particular, on the use of multidimensional scaling techniques [5], [6] to investigate the subjective effect of four impairments present simultaneously in various combinations. Specific questions which we attempt to answer are the following. 1) Was the perceptual space associated with the set of experimental conditions we employed unidimensional or multidimensional? 2) If multidimensional, what was the nature of the space? Did its dimensions merely correspond to the physical impairments, or did they imply the use by observers of other, possibly more general, psychological criteria? How did the dimensions relate to the commonly employed ratings of quality or preference [7]? 3) Was the analysis able to throw light on the nature of the impairments themselves or on the way in which they interacted with one another?

Manuscript received February 24, 1977; revised February 9, 1979. This work was supported by the Science Research Council, England.

J. S. Goodman was with the Department of Electrical Engineering Science, University of Essex, Colchester CO4 3SQ, England. He is now with the Post Office Psychological Services Division, London NW1 3DD, England.

D. E. Pearson is with the Department of Electrical Engineering Science, University of Essex, Colchester CO4 3SQ, England.

STIMULI

The particular system we investigated is illustrated in Fig. 1. High-quality 625-line 2:1 line-interlaced monochrome television pictures of 5.5 MHz bandwidth were derived from a flying-spot scanner. They were first subjected to simulated digital transmission by being coded into differential pulse code modulation (DPCM) form and then decoded into analog form once more. No transmission errors were simulated in the digital path, so that the impairment (denoted D) consisted solely of quantization error. Previous element prediction was used.

Subsequently, the signals were routed through an analog path in which there were, in order of occurrence, 1 μs positive echo (E), additive white Gaussian noise (N) band limited to 5.5 MHz, and band limitation (B) due to low-pass filtering of the signal. Each of the four impairments was introduced at one of two levels: the first level corresponded, as near as the laboratory apparatus permitted, to an invisible level of impairment and the second to a very visible level. The occurrence of a particular combination of impairments will be indicated by a letter-group of up to four letters: thus E indicates that the echo impairment was at its high-visibility level and all the others at low visibility, while $DENB$ indicates that all four impairments were simultaneously present at their high-visibility levels. Details of the four impairments are given in Table I.

A single test picture was used with many sharp high-contrast boundaries. This was quite a critical picture for three of the four impairments we used, namely D, E, and B. The fourth impairment N showed up quite adequately.

EXPERIMENTAL PROCEDURE

After passage through the simulated transmission link of Fig. 1, the pictures were displayed on a 20-in (50-cm) high-quality monochrome monitor in a curtained viewing area. The viewing conditions were set to conform as closely as possible to those recommended by the CCIR [7]. Observers were presented with pairs of impaired pictures, the first picture being shown for 4 s, followed by a blank screen for 0.3 s, followed by the second picture for 4 s. Each of the 16 impairment combinations was paired with itself and with each other impairment combination twice, the order of presentation being reversed the second time. This made a total of 256 different presentation pairs; 128 judgments were made at each of two 40-min sessions.

For each presentation pair, observers provided paired-comparison antiproximity data on a 7-point scale ranging from "identical 0" to "very dissimilar 6." No descriptions were given to the intermediate points, but observers were told that the scale was composed of equally spaced intervals. Sixteen practice pairs were given which were representative of the range subsequently encountered.

Twelve observers (six men and six women), drawn from the nonacademic staff and student population of the University of Essex, participated; each observer was given a simple test of both horizontal and vertical binocular grating acuity. None of the observers had had any previous experience in judging television

0018-9472/79/0600-0353$00.75

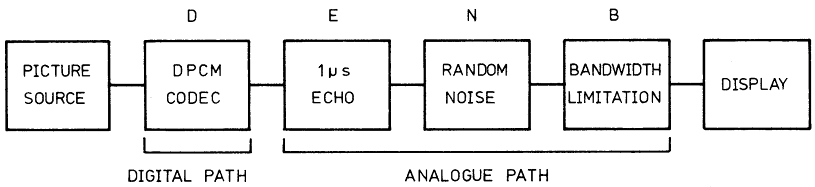

Fig. 1. Block diagram of simulated transmission link, showing order in which four impairments were introduced.

TABLE I
TECHNICAL DESCRIPTION OF THE IMPAIRMENTS

Impairment	Low-visibility level	High-visibility level
D (DPCM coding impairment)	16-level (4-bit) codec, 11 MHz sampling rate. Output levels* ±1/128, ±2/128, ±4/128, ±8/128, ±14/128, ±23/128, ±34/128, ±48/128.	6-level codec, 11 MHz sampling rate. Output levels* ±1/128, ±8/128, ±34/128.
E (Echo impairment)	No added echo.	Positive echo, delayed by 1 μs, added to signal. Peak-to-peak video signal adjusted to be the same with and without echo addition. Signal/echo ratio 8 dB.
N (Noise impairment)	Residual noise in flying-spot scanner. Estimated signal-to-noise ratio† 45 dB.	White Gaussian noise band-limited to 5.5 MHz added to signal. Signal-to-noise ratio† 20 dB.
B (Bandlimitation impairment)	Seventh-order elliptic function filter with phase correction, having 3 dB point at 5.6 MHz.	Fifth-order Gaussian filter with 3 dB point at 0.5 MHz, 6 dB point at 0.75 MHz.

* Figures refer to fractions of the peak white-to-black level video signal range.

† Unweighted (peak white-to-black level video signal)/(rms noise) ratio.

TABLE II
INDSCAL: ORDERED STIMULUS MATRIX

Dimension 1		Dimension 2		Dimension 3		Dimension 4	
Picture	Weight	Picture	Weight	Picture	Weight	Picture	Weight
E	.298	DEN	.305	DE	.223	DE	.367
DEB	.277	DN	.269	DEB	.216	E	.332
DE	.264	EN	.269	EB	.214	N	.283
EB	.253	N	.262	ENB	.177	DN	.238
ENB	.232	DNB	.217	DENB	.177	EN	.203
DEN	.221	DENB	.216	DEN	.133	DEN	.136
EN	.219	ENB	.182	EN	.134	O	.089
DENB	.175	NB	.177	E	.120	D	.045
O	-0.143	DEB	-0.068	DNB	.120	NB	-0.012
D	-0.172	EB	-0.147	NB	.117	B	-0.015
DB	-0.189	E	-0.172	DB	-0.003	DB	-0.098
B	-0.200	DE	-0.182	DN	-0.143	DNB	-0.14
N	-0.246	D	-0.286	B	-0.159	EB	-0.296
DN	-0.265	O	-0.304	N	-0.213	DEB	-0.320
NB	-0.361	DB	-0.366	D	-0.498	ENB	-0.376
DNB	-0.365	B	-0.372	O	-0.615	DENB	-0.433
Percentage of variance accounted for by the dimension	22%		22%		17%		12%

The dimensions were interpreted as dimension 1—the amount of stationary overlay patterning; dimension 2—the amount of moving overlay patterning; dimension 3—overall picture clarity; dimension 4—overlay patterning versus object distortion.

quality, but the experiments reported here were part of a longer series in which the same observers also made quality and preference judgments. Following the paired-comparison judgments, observers were asked to make quality and preference judgments of the multiply impaired pictures on which paired-comparison similarity judgments had been obtained.

DATA ANALYSES

Of the many analytic models which exist under the rubric of multidimensional scaling techniques, principal components analysis [8] and INDSCAL [9]–[11] were particularly appropriate to the similarity data of our study. Principal components analysis, which makes no assumptions about the structure underlying the observed data matrix, provided a trial dimensionality and starting configuration for the primary multidimensional analysis, INDSCAL. As the two techniques, principal components analysis and INDSCAL, gave essentially the same solution, we will present the results of the principal components analysis, with varimax rotation, only where it clarifies an ambiguity in the INDSCAL solution.

RESULTS

We obtained INDSCAL solutions in five, four, three, and two dimensions. We repeated this process three times in four and three dimensions utilizing a different trial starting configuration each time. With each starting configuration the best fitting solution accounted for approximately 76, 73, 71, and 61 percent of the total variance in the scalar products matrix for five, four, three, and two dimensions, respectively. The four- and three-dimensional solutions were readily interpretable. The four-dimensional solution was somewhat less reliable than the three-dimensional one over the three different starting configurations, particularly in the last dimension; however, on the basis of the principal components analysis, which yielded an almost identical solution with four eigenvalues greater than unity, we determined the four-dimensional solution to be a viable one. The stimulus matrix for the four-dimensional INDSCAL solution is presented in Table II.

There is no analytic technique available for naming or interpreting dimensions. It is a matter of art rather than science and is achieved by inspection of the factor structure or stimulus matrix and their pictorial representations, in the light of the attributes of the stimulus objects. The first dimension, which accounts for 22 percent of the variance, clearly divides those pictures which contain echo from those which do not. At one end of this dimension is the singly impaired echo picture *E*, characterized by a displaced ghost image or spatial overlay, and at the other *DNB*, a picture with blurring and coarse-grained noise. There are two possible interpretations for this dimension, neither without minor difficulties. First, the dimension can be considered to represent the amount of stationary spatial impairment, of whatever kind. The presence of B in the negative side of the dimension such a distance from E would militate against this interpretation, however, as both are stationary spatial impairments. The INDSCAL analysis does not separate EB and E by much along this dimension, although E produced a spatial overlay while EB had the result of severe blurring. However, the factor loadings for the equivalent principal components dimension are consistent with the stationary spatial overlay interpretation, the loadings being E 0.91270, DE 0.83446, EN 0.55828, DEN 0.52286, EB 0.40628, and DEB 0.37536. The appearance of the displaced ghost image was progressively less obvious as the loadings became less. The general form of the INDSCAL dimension plus the principal components solution leads us to select an interpretation of stationary spatial overlay for this dimension.

The second INDSCAL dimension also accounts for 22 percent of the variance. It clearly separates those pictures which contain random noise from the remaining stimuli. Bandwidth limitation following the addition of random noise reduces the noise power, and it can be seen that the four pictures with both noise and bandwidth limitation (Table II) are grouped together below those pictures with noise but without bandwidth limitation. This second dimension, therefore, appears to correspond to the visibility of an overlay pattern with both temporal and spatial components, i.e., a moving pattern.

The third INDSCAL dimension accounts for 17 percent of the variance in the analysis. This dimension has at its lower end (Table II) the unimpaired picture 0 and at its upper end DE, DEB, and EB, all severely impaired pictures. Overall, INDSCAL dimension 3 seems to correspond to picture clarity, i.e., to whether the picture is clearly seen through a transparent medium or whether the medium is distorting the picture in some way.

Twelve percent of the variance in the analysis is accounted for by the fourth dimension. Inspection of column 4 of Table II indicates that bandwidth limitation impairments are grouped together on the negative side of this dimension, while additive impairments such as echo and noise are at the positive end. This dimension appears to be separating those impairments which cause the integrity of the objects in the picture to be destroyed from overlay types of impairment.

A multiple regression program, PROFIT,[1] used to examine the relationship between the dimensions of the INDSCAL solution and the mean values of observers' preference ratings for the 16 pictures, revealed a good fitting vector $r = 0.86$. The direction cosines of the fitted vectors in the normalized space were 0.02321 for stationary overlay patterning, -0.4295 for amount of moving overlay patterning, -0.8477 for overall picture clarity, and 0.2073 for the object distortion versus overlay dimension. Clearly the overall clarity dimension is the most important one in terms of observer preference when mean preference ratings are considered.

Discussion

Dimensionality of the Space

Clearly, the INDSCAL analysis indicated that observers were employing more than one dimension. This finding was supported by the principle components analysis.

Interpretation of the Dimensions and Nature of the Space

It is of interest to compare the overall dimensionality with that obtained by McDermott [12] in her classic study of singly impaired analog acoustical circuits. McDermott found that three dimensions were sufficient to explain listeners' judgments of perceived circuit similarity, which she interpreted as 1) overall clarity, 2) a distinction between signal distortion and background distortion, and 3) subjective loudness. In the television case, a dimension of brightness or contrast, corresponding to loudness in the speech case, would not normally be expected to occur, as television signals have their black-to-white signal range held constant during transmission. Hence, particularly in our own case, where we used a single test picture kept at constant peak luminance and contrast, no dimension corresponding to McDermott's third dimension emerged. McDermott's other two dimensions of overall clarity and signal-background distortion appear to correspond quite well, however, with dimension 3 and dimension 4, respectively, in the INDSCAL analysis.

The remaining two dimensions (1 and 2) in the INDSCAL analysis appear to indicate that observers were using further distinctions relating to the nature of the overlay pattern. These two dimensions did not appear in the auditory case, possibly in part as a result of the inherently different physical dimensionality of television pictures and telephone speech. In a recent study of digital speech processing [13], McDermott *et al.* found, with an equalized mean power level, that observers dealing with the nature of their temporal patterning attended to less obvious differences in the impairments. As well as reproducing the earlier finding [12] of an overall clarity dimension and signal distortion versus background dimension, McDermott *et al.* identified a third dimension which corresponded to the continuous versus interruptive nature of the impairment.

Another question we posed concerned the relationship of the obtained dimensions to the observers' preference for the variously impaired pictures. Overall picture clarity was clearly most important to subjective preference ratings. The study of McDermott *et al.* [13] has this same result.

Nature of the Impairments and Their Interaction

The differential coding impairment D, occurring singly, which produced edge busyness, streaking, and contouring, was not seen by observers as being very different from the unimpaired picture 0, being differentiated from 0 mainly along the clarity axis, dimension 3. In combination with other impairments, D tended, with an exception in each case, to move the combination a small way towards the positive end of dimension 2 and/or towards the negative end of dimension 4, indicating that its effect is to increase the scintillating noise content slightly and/or to distort objects in the picture. These movements are all small, however, and by and large D tended to be swamped by the other impairments. Thus the evidence, such as it is, points to quantizing distortion introduced by a differential pulse code modulator as being of a multidimensional nature.

The echo impairment E, when added to the unimpaired picture 0 or any other combination of pictures, produced a large positive shift along dimension 1. The primary effect of the noise N was that of a large positive shift on dimension 2, the magnitude of this shift being reduced when followed by B. On dimension 4 its influence is interesting, in that when added to 0 or D it increased the overlay impairment, but added to E, DE, EB, or DEB, it decreased the overlay impairment, pushing the combination towards the object-impairment end of the dimension. This is probably due to the masking effect it has on the strong overlay produced by E.

The band-limitation impairment B, like the coding impairment D, is differentiated from the unimpaired picture 0 mainly along the clarity axis (dimension 3). It shifts 0 only a small distance towards the object-impairment end of dimension 4, but shifts other impair-

[1] This analysis was included at the suggestion of B. J. McDermott of Bell Laboratories. The authors are grateful for her assistance in this matter.

ments such as N, DN, E, and EN a large amount in the same direction. Thus B is an interesting impairment, appearing to affect the dimensional position of impairments added before it more than it does the original picture.

Although we have not yet investigated this point experimentally, it appears likely from the above observations that the dimensional character of any impairment combination will be affected by the order in which the impairments are introduced. Impairments which are physically independent in nature appear to interact when introduced into the same television picture.

Conclusions

Multidimensional scaling analysis indicated that observers participating in our experiments used four dimensions in their characterization of the impairments. We interpreted the dimensions as 1) overall picture clarity, 2) a distinction between overlay impairment and object impairment, 3) the amount of purely spatial or stationary overlay patterning, and 4) the amount of spatiotemporal or moving overlay patterning. Our knowledge of whether these dimensions are used more generally by observers when judging impaired television pictures must await further experimentation with a wider selection of impairments than we ourselves employed.

Something of the individual character and interaction of the four basic impairments was revealed by the analysis. The primary effect of echo and noise was to provide an overlay pattern on the picture, stationary in the case of echo and moving or scintillating in the case of noise. The character of the differential quantizing noise was more complex, having components along three dimensions, those of overall clarity, moving overlay patterning, and object-overlay distortion. The character of the band-limitation impairment appeared to be that of a modifier of the character of previous impairments, its effect when introduced singly being mainly along the clarity dimension, with a smaller component along the object-overlay dimension. The interaction between the four impairments was complex but interpretable.

The study points to a possible binary classification of television impairments depending on whether they distort objects in a picture or whether they mask these objects by means of an overlay pattern. A further subdivision of masking impairments into moving and stationary types is suggested.

Certain fundamental factors or dimensions appear to be emerging from the application of multidimensional scaling to acoustical and visual communication systems. Judgments of similarity and preference/quality on both analog and digital impairments introduced singly and multiply in both sensory modalities appear to yield comparable results.

Acknowledgment

The authors would like to record their thanks to Mr. J. A. Allnatt, Dr. J. E. Thompson, Ms. G. Reid, and Mr. T. White of the British Post Office Research Department for very helpful discussions and to Dr. D. J. Goodman and Ms. B. J. McDermott of Bell Laboratories for invaluable advice and assistance with multidimensional scaling programs. The experimental work was conducted with the technical assistance of Mr. M. Brown and Mr. T. Quinlan of the Visual Systems Research Laboratory, University of Essex.

References

[1] N. W. Lewis and J. W. Allnatt, "Subjective quality of television pictures with multiple impairments," *Electron. Lett.*, vol. 1, pp. 187–188, 1965.
[2] J. R. Cavanaugh and A. M. Lessman, "Subjective effects of differential gain and differential phase distortions in NTSC color television pictures," *J. Soc. Motion Pict. Telev. Eng.*, vol. 80, pp. 614–619, 1972.
[3] C. A. Siocos, "Subjective impairment of television pictures—Considerations regarding the summability of impairment units," *J. Soc. Motion Pict. Telev. Eng.*, vol. 81, pp. 917–920, 1972.
[4] J. W. Allnatt, "Opinion-rating model applied to television-transmission-system studies," in *Proc. IEE*, vol. 122, no. 8, pp. 769–774, 1975.
[5] R. N. Shepard, A. K. Romney, and S. B. Nerlove, *Multidimensional Scaling*. New York and London: Seminar Press, 1972.
[6] E. J. Jackson, "Scaling techniques for subjective judgments of image quality," *J. Soc. Motion Pict. Telev. Eng.*, vol. 83, pp. 891–894, 1974.
[7] *CCIR Recommendation 500*, "Method for the subjective assessment of the quality of television pictures," XIIIth Plenary Assembly, Geneva, 1974.
[8] W. W. Cooley and P. R. Lohnes, *Multivariate Data Analysis*. New York: Wiley, 1971.
[9] D. J. Carroll and J. J. Chang, "Analysis of individual differences in multidimensional scaling via an N-way generalization of 'Eckart–Young' decomposition," *Psychometrika*, vol. 35, pp. 283–319, 1970.
[10] D. J. Carroll and M. Wish, "Models and methods for three-way multidimensional scaling," in *Contemporary Developments in Mathematical Psychology, Vol. II*, D. H. Krawtz, R. C. Atkinson, D. R. Luce, and P. Suppes, Eds. San Francisco: Freeman, 1974.
[11] W. S. Torgerson, *Theory and Methods of Scaling*. New York: Wiley, 1972.
[12] B. J. McDermott, "Multidimensional analyses of circuit quality judgments," *J. Acoust. Soc. Amer.*, vol. 45, pp. 774–781, 1969.
[13] B. J. McDermott, C. Scagliola, and D. Goodman, "Perceptual and objective evaluation of speech processed by adaptive differential PCM," *Bell Syst. Tech. J.*, vol. 57, pp. 1597–1618, 1978.

Failure Prediction for an On-Line Maintenance System in a Poisson Shock Environment

K. S. LU AND R. SAEKS, FELLOW, IEEE

Abstract—**A failure prediction algorithm for application in a periodic on-line maintenance system operating in a Poisson shock environment is described. The system under test is measured at periodic maintenance intervals with the data derived therefrom being used to estimate system lifetime and determine an optimal replacement time. The resultant algorithm is simulated and compared with various fixed replacement schedules.**

I. Introduction

Although considerable effort has been expended during the past decade to develop techniques for fault detection and diagnosis in both analog and digital electronic circuits [10], little attention has been given to the possibility of formulating algorithms for fault prediction. To accurately predict a fault, a device must be tested at periodic maintenance intervals. If the device fails or does not operate correctly, it is replaced immediately. The device may be assumed good if its characteristics are in tolerance. However, if the characteristics are slightly off nominal but the device still operates correctly, one can attempt to predict if the device will fail before the next scheduled maintenance interval. If device failure is predicted, it can be replaced before failure occurs as part of planned preventative maintenance.

Manuscript received April 3, 1978; revised September 18, 1978 and February 1, 1979. This work was supported in part by the Joint Services Electronics Program at Texas Tech University under ONR Contract 76-C-1136.
R. Saeks is with the Department of Electrical Engineering, Texas Tech University, Lubbock, TX 79409.
K. S. Lu is with the Texas Instruments Incorporated, Dallas, TX.

0018-9472/79/0600-0356$00.75