Journal of Experimental Psychology:
Human Perception and Performance
1980, Vol. 6, No. 2, 277–289

Variability and Sequential Effects in Cross-Modality Matching of Area and Loudness

John C. Baird
Dartmouth College
David M. Green and R. Duncan Luce
Harvard University

Individual subjects' performance was examined for cross-modality matching (CMM) of loudness to visual area, as well as for magnitude estimation (ME) of the component continua. Average exponents of power functions relating response magnitude to stimulus intensity were .73 for area, .20 for loudness, and 2.44 for CMM. Predictions of the CMM exponent based on ME were higher than the empirical values, whereas more accurate predictions were made from magnitude production exponents obtained in a previous study. Sequential dependencies were assessed by comparing the response on trial n to the response on trial $n-1$. The coefficient of variation of the response ratio R_n/R_{n-1} was systematically related to the stimulus ratio S_n/S_{n-1} for both area and loudness. The coefficient was lowest for ratios near 1 and increased for larger or smaller values. For CMM, the coefficient of variation appeared to be independent of stimulus ratios. The correlation between log R_n and log R_{n-1} was also related to S_n/S_{n-1} for both ME and CMM. The correlation was highest when S_n/S_{n-1} was 1 and dropped to 0 with increasing stimulus separation, but CMM yielded a shallower function than ME.

In recent years we, and others, have studied magnitude estimates (ME) of individual subjects, using a sizable number (about 20) of stimuli that were each presented frequently (about 100 times) for judgment by the subjects, who had been instructed to preserve subjective ratios in their responses (Baird, 1970; Green & Luce, 1974; Green, Luce, & Duncan, 1977; Jesteadt, Luce, & Green, 1977; Ward, 1973). In addition, in one publication (Green et al., 1977) we also studied magnitude production (MP). Until very recently, cross-modality matching (CMM) for individual subjects has been lacking. Ward (1975, 1979) reported on the matching of time duration to loudness and on duration matched to the distance between two dots, and Painton, Cullinan, and Mencke (1977) studied individual functions based on pitch-duration matches. Here we report data on matching loudness to area.

The types of data analyses we use are those that have evolved in the articles on ME. First, we look at mean response functions (logarithmic coordinates), and as was suggested by Stevens (1975, chap. 4), we ask whether the CMM results are predictable from the ME data obtained for each modality separately. This has been found to be approximately true for group averages, but seldom has been studied for individual subjects. Second, we look at the variability of the responses. We do this both for the responses as a function of the stimulus presented, and, more importantly, we study the coefficient of variability of the

We appreciate the assistance of Sam Pilato and Fred Smith in the procedural and analysis phases of this study.

Requests for reprints should be sent to John C. Baird, Department of Psychology, Dartmouth College, Hanover, New Hampshire 03755.

ratio of responses on successive trials for both ME and CMM. The latter is of interest because we have shown, both for ME and MP, that when the coefficient of variation of response ratios is plotted as a function of the corresponding signal ratio (or separation in decibels), a characteristic V pattern results. The minimum of the V occurs when the signal separation is small, and it is larger by a factor of from three to five than when the signal separation is large. Third, we study the correlation in the logarithm of the responses on successive trials. This quantity is expected to be large if the subjects are complying with the instructions to preserve subjective ratios in their responses (see Luce & Green, 1974). For ME and MP, this correlation as a function of signal ratio is, in fact, an inverted V, with a maximum of from .70 to .90 for small signal differences and a minimum in the neighborhood of 0 for large differences.

Not only are we interested at a purely empirical level in whether or not the same patterns obtain for CMM, but considerable theoretical interest attaches to the source or sources of these two unanticipated V patterns. After many years of investigation, a satisfactory model of magnitude (ratio) estimation has not been forthcoming. We feel that a key to further progress in this regard lies in a fuller understanding of response variability and sequential response dependencies together with attention to measures of central tendency. The more diverse our data base concerning direct estimation of sensory magnitudes, the more focused can be our search for possible theoretical mechanisms at both the psychological and physiological levels.[1]

Method

Subjects

The subjects were two students and one of the present authors (JB). The students were paid $3.50 per hr for their participation. None of the subjects had previously taken part in experiments employing the particular stimuli and procedures used here, although JB had experience with the methods of ME and CMM.

The study consisted of three parts: (a) magnitude estimation of visual area, (b) magnitude estimation of loudness, and (c) cross-modality matching of loudness to visual area. The order of tasks was a, c, b for each subject, with from 100 to 200 practice trials run on each task before data were collected for analysis.

Estimation of Visual Area

The stimuli were computer generated, random, outline shapes displayed on a television monitor (22.9-cm diameter screen). There were 21 different areas, ranging in size from .381 cm^2 to 76.35 cm^2 in equal logarithmic steps. The subject sat with his eyes approximately $\frac{3}{4}$ m from the screen in a single-walled, sound-treated chamber. The visual angles of the targets ranged from ~.26° to ~3.8°. A set of 50 different shapes was generated for each area and stored in a computer file for random selection during the course of a particular series of 100 trials.

Each shape was produced as follows: Two concentric circles were produced, the inner one having a radius one third that of the outer one. Both circles then were divided into 10 equal parts by passing five diameter lines through their centers. A point was chosen at random within one of the sections described by two of the diameter lines and the boundary arcs of the circles. This was done for each of the 10 sections, and a solid line was drawn connecting the points. The resulting outline figure was adjusted in size to produce the area requirement for that particular stimulus. The actual stimulus was first imaged by a Tektronix scan converter (type 4501), controlled by a PDP-9 computer, and subsequently the figure was presented for 500 msec on the television screen.

Numerical responses were typed by the subject on a special response box containing 12 keys (digits 0–9, a decimal point, and two control functions). Mistakes could be cleared and another number entered. When the subject was satisfied with his response, he depressed a control key, the response was recorded by the computer, and the next trial was initiated. Subjects were instructed to judge the area of each stimulus in respect to a standard and to assign numerical responses to reflect this ratio. All integers from 1 to 99,999 were permissible responses. Runs consisted of 100 trials, with subjects completing between four and six runs separated by rest periods in a 2-hr session. Approximately 2,500 trials were conducted over a 1-wk period.

The standard stimulus, assigned the modulus value of 100, was located at the geometric mean (5.4 cm^2) of the series and was presented for 10 sec before each block of 100 trials. Subsequent stimuli were selected randomly from among the 21 possible areas and from among a set of 50 possible shapes for each area.

Estimation of Loudness

The stimuli were 1,000-Hz tones of 500-msec duration, presented binaurally, in quiet, via TDH-39

[1] We plan to address these theoretical issues more extensively in a future article.

headphones. The test room was single walled and sound treated (IAC-402 A), but it was not the same room used in ME of visual area. The response box was also somewhat different, although it permitted the same computer storage of numerical values and automatic control of time intervals between trials. The procedure was self-paced, with the response to the stimulus initiating the next trial.

The 21 stimulus intensities ranged from 40 to 90 dB (SPL) in 2½-dB steps and were chosen at random for presentation on a given trial. A standard tone of 65 dB was assigned the modulus value of 100 and was presented for 10 sec before each run of 100 trials. Subjects were instructed to assign numerical values to subsequent stimuli such that their responses reflected the perceived ratio of the stimulus intensity with respect to the standard. All integers from 1 to 99,999 were permissible responses. Subjects completed between four and six runs over a 2-hr session, with several minutes rest after each run. Approximately 2,500 trials were conducted over a 1-wk period.

Cross-Modality Matching

The stimulus continuum was represented by the 21 visual areas used in the ME task. The response continuum under the subject's control was the intensity of a repeating 1,000-Hz tone (on for 500 msec, off for 100 msec). Matching data were collected in the room used for the ME of area.

Initially, the standard area was presented for 10 sec on the video screen while the standard sound intensity was heard through the earphones. These two stimuli were the same standards used in the ME tasks. The subject was told to assume that the loudness of the standard tone matched the standard area and that subsequent areas should be matched by tones so that the ratio of the tone with respect to its standard was the same as the ratio of the area with respect to its standard. At first, this proved difficult, but after a few runs, the tones were easily matched to the areas. Subjectively, it did not appear that numbers entered into this judgment in any way. That is, subjects did not report that they first estimated the numerical ratio of the area to the standard and then produced the same numerical ratio of the sound in respect to its standard. The matching procedure seemed more direct and in agreement with Stevens' (1975, pp. 110–111) view of CMM.

On each trial an outline shape (chosen randomly from among the 21 possibilities) was presented on the screen and remained there until the subject was satisfied with his adjustment of the sound intensity. The starting intensity of the tone was chosen at random in the range of 40–90 dB with 1-dB steps. The subject could adjust the intensity by pushing one of four buttons on a response box; two of the buttons provided coarse adjustment of the tone in randomly chosen steps of 4, 5, or 6 dB, one button increasing and the other decreasing intensity. The other two buttons produced increasing or decreasing 1-dB changes in intensity. The lower limit of sound intensity permitted by the equipment was 40 dB (SPL), the upper limit, 105 dB (SPL). Once the subject achieved the desired intensity, he pushed a control button that cleared the screen, shut off the tone, and initiated the next trial. Runs of 50 trials were conducted with brief rest periods after each run. From 8 to 10 runs were conducted over a 2-hr session, with approximately 2,500 trials conducted over a 1-wk period.

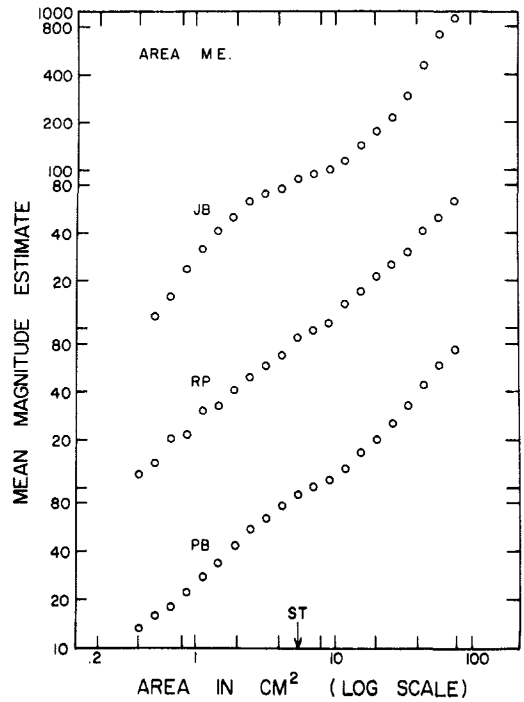

Figure 1. Mean magnitude estimates (M.E.) as a function of target area (cm²) of a random outline shape. (In this and in all succeeding figures, both coordinates are logarithmic, the small arrow ST represents the standard, and to keep the data from overlapping, the ordinate is repeated for each subject. JB, RP, and PB refer to subjects.)

Results and Discussion

Mean Responses

The arithmetic means of the judgments for each stimulus were computed separately for each subject. In the case of ME, the arithmetic mean of the numerical responses is recorded for each subject. In CMM the mean decibel setting is recorded. Figures 1, 2, and 3 show these means plotted against area (cm²), sound intensity (SPL), and area (cm²), respectively. The coordi-

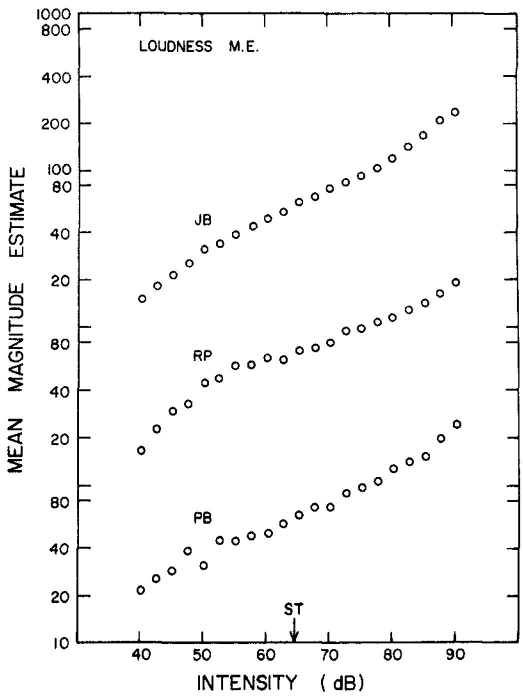

Figure 2. Mean magnitude estimates (M.E.) of loudness as a function of sound intensity (SPL) of a 1,000-Hz tone. (JB, RP, and PB refer to subjects. ST represents the standard.)

nates are logarithmic, and values on the ordinate are translated upward to separate the data of the three subjects.

Most of the functions are fairly straight on the log–log plot indicating that the antilog of the stimulus and response values can be adequately described by a power function $R = kS^{\gamma}$ in which R is the response magnitude, S is the stimulus intensity (units of power not pressure), k is a constant (antilog of the intercept on the ordinate), and γ is the exponent (slope). Estimates of the exponents (γ) and constants log (k) were obtained by least squares solutions to determine the best-fitting straight lines for each function. The exponents are presented in Table 1. The values are similar across subjects for the ME functions, but vary somewhat for CMM. The average exponent of .73 for area falls within the range of values found previously, although our exponents are near the low end of that range (cf. Baird, 1970, Table 3.3. pp. 50–51; Teghtsoonian, 1965). The average exponent of .20 for loudness is the same as the value found earlier by Green et al. (1977), who employed a similar procedure; however, it is somewhat lower than the exponents generally reported by other investigators (~.3 for power or energy units; Baird & Noma, 1978, Table 5.1, p. 83). It seems that exponents are lower for individual subjects run on a large number of trials as compared with exponents based on groups of subjects, each of whom gives only a few judgments for each stimulus. At present, we do not understand the reason for this difference.

We are not aware of other studies in which loudness was matched to visual area, so the values in Table 1 cannot be compared with earlier work in this respect. However, it is possible to derive predictions of the CMM exponents based on the ME results obtained here as well as on MP data obtained under similar conditions (Green et al., 1977). The two data sets do not

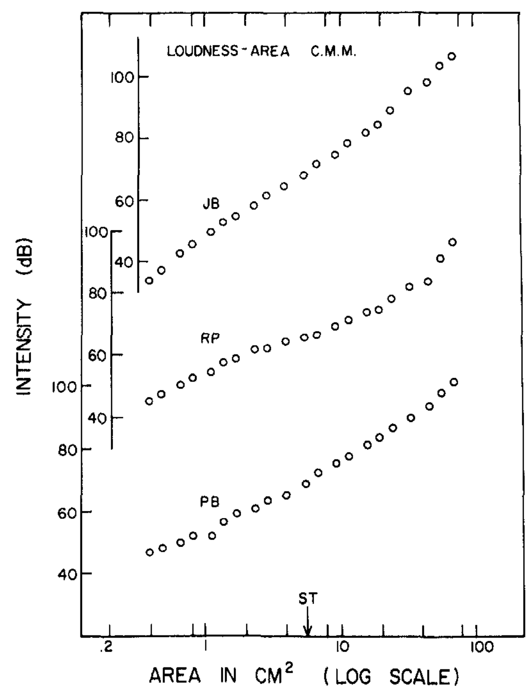

Figure 3. Mean cross-modality matches (C.M.M.) of the loudness of a 1,000-Hz tone to the area of a visual shape. (The adjusted sound intensity [SPL] is plotted as a function of the area of the shape [cm²]. JB, RP, and PB refer to subjects. ST represents the standard.)

Table 1
Empirical Exponents for ME and CMM and Predicted Exponents for CMM

	ME		CMM		
	Visual area	Loudness (dB)	Empirical	Predicted, ME	Predicted, MP
Subjects					
JB	.75	.22	3.04	3.41	2.07
RP	.72	.18	1.91	4.00	2.42
PB	.72	.19	2.36	3.79	2.30
M	.73	.20	2.44	3.73	2.26

ME = magnitude estimation; CMM = cross-modality matching.

yield the same predictions, so both derivations are presented. Let us assume with Stevens (1975) that the exponent for CMM can be predicted by the *estimation* exponents for the component continua.

We might assume that each physical stimulus is mapped to a number, then the numbers are equated; hence (neglecting the constant k) if $R_1 = S_1^{\gamma_1}$ is the function relating loudness to intensity and $R_2 = S_2^{\gamma_2}$ is the function relating perceived area to physical area, then when R_1 matches R_2 we find $S_1 = S_2^{\gamma_2/\gamma_1}$. That is, physical intensity is related to physical area with an exponent equal to the ratio of the ME exponents, say $\gamma' = \gamma_2/\gamma_1$. This argument assumes that CMM involves two magnitude estimations; hence, the exponent is listed in Table 1 as the CMM prediction (estimation). The predictions are uniformly higher than the empirical values, and with the exception of JB, the discrepancy is considerable.

One can also argue that the physical area elicits a response, assume that it is a number at the present, and assume that number in turn elicits a matching physical intensity. In short, the area is magnitude estimated as $R_2 = S_2^{\gamma_2}$, but this response is used as the stimulus for a magnitude production of intensity. The formula would be $S_1 = R_2^{1/\gamma_1''}$, in which γ_1'', the MP exponent, is not necessarily equal to γ_1, the ME exponent. Green et al. (1977), for example, found $\gamma_1 = .20$, whereas γ_1'' was .33 for the same five observers. Since our observers also produced an average ME exponent of .20, we will simply assume that their MP exponent would be larger by the ratio of .33/.20. Using this estimate of γ_1'', we can predict the CMM exponent using the ME-to-MP transformations as listed in the last column of Table 1. Neither set of predictions correlates over subjects very well with the actual data, but the second line of argument (at least the means of ME-MP-CMM) seems to be somewhat closer. Unfortunately, individual subjects are highly variable in the ratio of ME to MP exponents; hence, our correction of .33/.20 is probably not very accurate.

Variability of Responses

Although the power law adequately describes the trend of the mean data, a deeper understanding of psychophysical judgment may require further understanding of the nature and underlying causes of response variability. In the present experiment, there are several potential sources of variability, including the stimulus intensity itself, the location of the standard stimulus in the series and other anchors (such as the smallest and largest stimuli), and the intensity of the stimulus presented on the previous trial. The last source has been emphasized in earlier studies and will receive most attention here (Green et al., 1977; Jesteadt et al., 1977; Luce & Green, 1978). Before turning to this issue, however, the effects of the other sources of variability will be summarized.

A common measure of response variability is the relative error or coefficient of variation (standard deviation divided by the arithmetic mean). This statistic has been employed in a variety of psychophysical contexts and has received wide acceptance

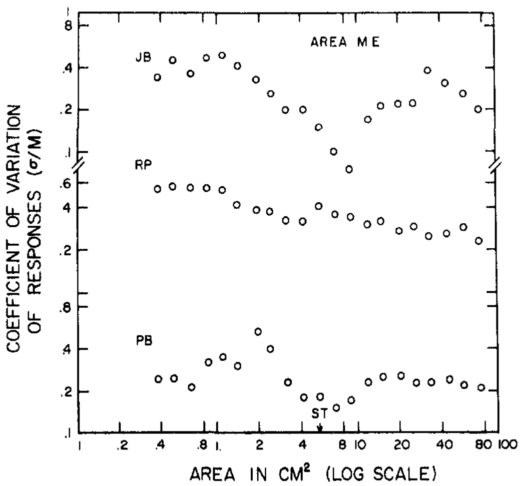

Figure 4. Coefficient of variation (σ/M) of magnitude estimates (M.E.) of visual area as a function of the area (cm²) of a random outline shape. (JB, PR, and RB refer to subjects. ST represents the standard.)

as an indication of the variability of numerical magnitude estimates (e.g., Baird, 1970; Baird, Kreindler, & Jones, 1971; Luce & Green, 1974; Mashhour, 1964).

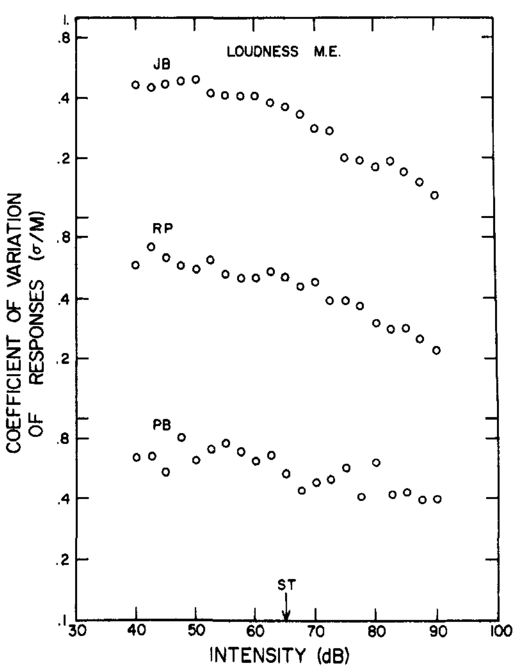

Figure 5. Coefficient of variation (σ/M) of magnitude estimates (M.E.) of loudness of a 1,000-Hz tone as a function of sound intensity (SPL). (JB, RP, and PB refer to subjects. ST represents the standard.)

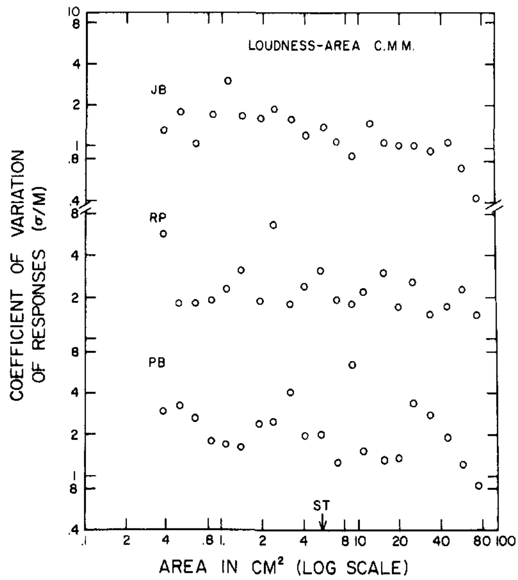

Figure 6. Coefficient of variation (σ/M) of cross-modality matches (C.M.M.) of loudness of a 1,000-Hz tone as a function of the area of a random shape. (Computations are based on the responses in power units, transformed from the decibel settings by $R = 10^{dB/10}$. JB, RP, and PB refer to subjects. ST represents the standard.)

More recently, the statistic also has been applied to magnitude production data, in which loudness is the dependent measure (Green et al., 1977).

Returning to the present experiment, the coefficient of variation was computed for the numerical responses given to each stimulus intensity. Results for ME are presented in Figures 4 and 5 (logarithmic coordinates). In general, the coefficient of variation is greatest for the smallest stimulus value and progressively decreases as stimulus intensity increases. For estimation of visual area (Figure 4), there is a dip in the function for two subjects near the location of the standard. A dip at the standard is commonly reported for judgments of visual area (reviewed by Baird, 1970). Since the coefficient of variation appears to increase with increasing separation of a stimulus from the centered standard, the overall function is referred to as a V-shaped pattern. The third subject shows a continuous decline of the coefficient of variation with increases in stimulus area; no dip at the standard is evident. The same gradual

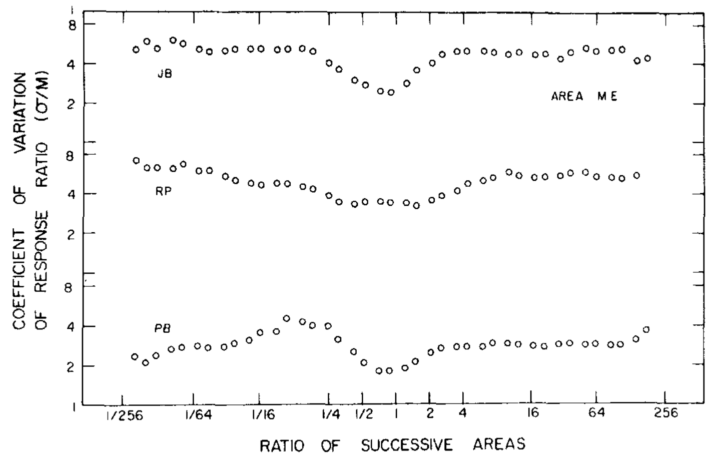

Figure 7. Coefficient of variation of response ratio (σ/M) as a function of the ratio of stimulus areas on trial n and $n - 1$. (A ratio of 1 represents the case in which the same stimulus was presented in succession. Each point is based on all magnitude estimates (M.E.) for a given stimulus ratio, regardless of the stimulus pair producing that ratio. JB, RP, and PB refer to subjects.)

decline in variability is also present for all three subjects when estimating loudness (Figure 5), but the range of numbers is different, and no dip at the standard is apparent. These results agree substantially with those reported by Green et al. (1977).

To compare the results for CMM with those for ME, the decibel settings were transformed into power units (R) by the formula $R = 10^{dB/10}$. Results are shown in Figure 6. The coefficient of variation declines slightly with increasing stimulus intensity, but the functions are more ragged than those for ME, and the overall level of variability is much higher.

Variability of Response Ratios on Successive Trials

The coefficient of variation also may be computed on the ratio of the response magnitude on trial n to the response magnitude on the previous trial ($n - 1$). In earlier studies it was shown that variability computed in this manner demonstrates a V-shaped pattern when plotted as a function of intensity separation between stimulus n and stimulus $n - 1$ (Green et al., 1977; Luce & Green, 1974). This pattern should not be confused with the V shape obtained for raw responses as a function of stimulus intensity (Figure 4). In the present context, the low point of the V occurs when the same stimulus is presented on successive trials; increasing stimulus separation in either a positive or negative direction leads to an increase in relative error. This was true in the present experiment for ME but not for CMM.

The calculations determine the mean and standard deviation of the response ratio R_n/R_{n-1} for each stimulus ratio (separation in logarithmic units). For ME this calculation is based simply on the ratio of numerical responses. For CMM we first transform decibel settings into power units before finding the response ratio as $R_n/R_{n-1} = 10^{(dB_n - dB_{n-1})/10}$.

The coefficient of variation is shown in Figures 7, 8, and 9, plotted against the ratio of successive areas (Figures 7 and 9) or against the decibel difference in successive sound intensities (Figure 8). The V-shaped pattern is evident for ME of visual area and loudness for all three subjects, although the minimum coefficient of variation does not always occur at a stimulus ratio of 1 (or 0 decibel separation). The ends of the stimulus scale appear to anchor judgments to some extent, since relative error is lower there in several of the functions (especially for loudness).

On the other hand, the V-shaped pattern is absent for CMM; the functions are rag-

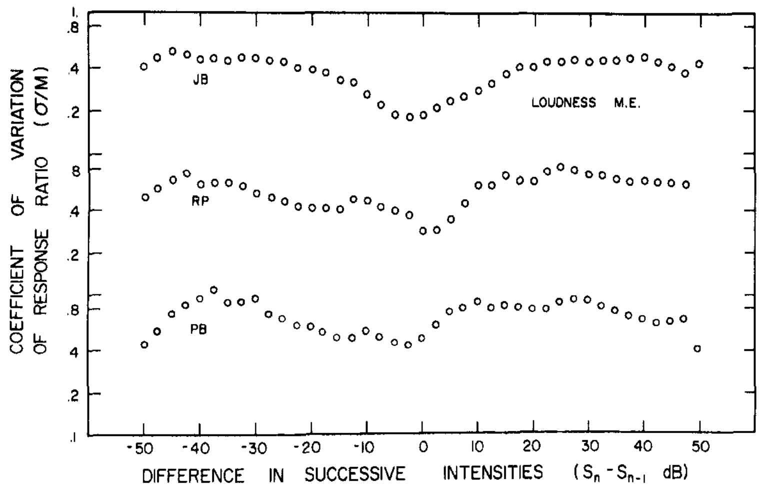

Figure 8. Coefficient of variation of response ratio (σ/M) as a function of the logarithmic difference in sound intensity (SPL) on trial n and $n - 1$. (Each point is based on all magnitude estimates (M.E.) for a given stimulus separation, regardless of the stimulus pair producing that ratio. JB, RP, and PB refer to subjects.)

ged for all three subjects and have minimum relative errors at the largest stimulus ratio. Moreover, the overall coefficient of variation is larger than for ME by a factor of from 5 to 10. This is the only instance we know of where the V-shaped pattern is so thoroughly lacking. The explanation of this finding cannot rest with the differences between a task requiring production of magnitudes and one requiring estimation of magnitudes. Although variability in MP is greater than for ME, the V-shaped pattern still obtains (Green et al., 1977, p. 452, right panel of Figure 3).

Green and Luce (1974) proposed that the dip in the relative variability for ME arises because there is an attention band, about 15–20 dB wide for loudness, of variable location and with the following key property: A signal falling within the band is repre-

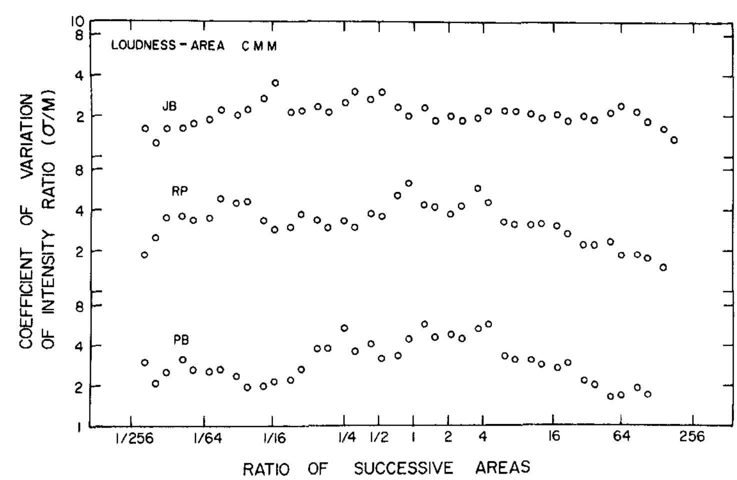

Figure 9. Coefficient of variation of sound intensity ratio (σ/M) as a function of the ratio of stimulus areas on trial n and $n - 1$. (Data are from cross-modality matching [C.M.M.]. A stimulus ratio of 1 represents the case when the same area is presented on successive trials. Calculations of the coefficient of variation were done after transforming the decibel settings into power units. JB, RP and PB refer to subjects.)

sented in the central nervous sytem by a sample size about an order of magnitude greater than when the same signal falls outside the band. Further, Green and Luce postulated that the band tends to be located in the region of the immediately preceding signal. Together, these phenomena account for the observed dip. Much the same mechanism is thought to occur in MP. If we assume that CMM arises essentially by a production following an estimation, the V pattern will occur only if each band, one for each modality, lies in the correct location. Since each can be related to the signals only through their internal representation, which is, of course, variable, then there must be some blurring or attenuation of the phenomenon. Whether this explanation is sufficient to account for the results cannot be assessed without developing detailed models for both ME and MP. We have worked fairly intensively on models for estimation (Luce, Baird, Green, & Smith, Note 1), and so far our attempts to simulate the production process have had no success. So, presently, we cannot determine if the blurring resulting from the combination of ME and MP is adequate to account for what we have observed. It should be emphasized that the overall variability of the CMM data is rather larger than one would have guessed based on the known ME data, but again this is only a guess, since we do not have the necessary model to make an exact prediction.

Sequential Effects: Correlation of Successive Responses

The instructions to the subject in ratio estimation and production techniques emphasize that perceived ratios among stimulus intensities should be preserved in the stated or produced responses. If subjects followed these instructions and if the stimulus on trial $n - 1$ served as a referent, we would expect a high correlation between responses on trial n and responses on trial $n - 1$. When such a correlation occurs, the response ratio hypothesis is verified (Luce & Green, 1974). In a series of recent experiments involving ME, MP, and CMM, the validity of the response ratio hypothesis has been shown to depend critically on the stimulus ratio (S_n/S_{n-1}). High correlations ($\sim$.7 to .9) of log R_n and log R_{n-1} occur when stimuli are similar in magnitude on successive trials, whereas the correlation drops to zero or even to a negative value when stimuli are widely separated (Green et al., 1977; Jesteadt et al., 1977; Luce & Green, 1978; Ward, 1979). Intermediate separations of stimuli on successive trials produce intermediate correlations, thus leading to an inverted-V function when the correlations are plotted against differences (or ratios) in successive stimulus intensities. In view of the possible link between the inverted V and the V shape obtained for the variability of response ratios over successive trials (Luce & Green, 1978), it seems important to determine the details of this supposed linkage for the present experiment; especially for CMM, in which the V-shaped pattern of variability is not present (Figure 9).

The calculations are based on the following considerations: Since each of 21 different stimuli can be presented on trial n and on trial $n - 1$, the domain of possible sequences (one trial back) is represented by a 21×21 matrix of stimulus pairs. The correlation between log R_n and log R_{n-1} was computed for each cell of this matrix, and the results were then averaged across stimulus pairs of the same separation (ratios). Three technical points should be noted in this regard. First, for ME of area and loudness, the logarithms of the numerical responses were calculated before determining the correlation, but the results are practically unchanged if the correlation is based on the original responses. Second, for CMM the correlation analysis is performed directly on the adjusted response values, since these are already in logarithmic units (decibels). Third, to avoid a statistical artifact, it is important that the correlation be computed separately for each stimulus pair in the 21×21 matrix and then averaged across pairs with the same stimulus separation (ratio). If, for example, the responses for all stimulus ratios of 1 (same stimulus presented on successive

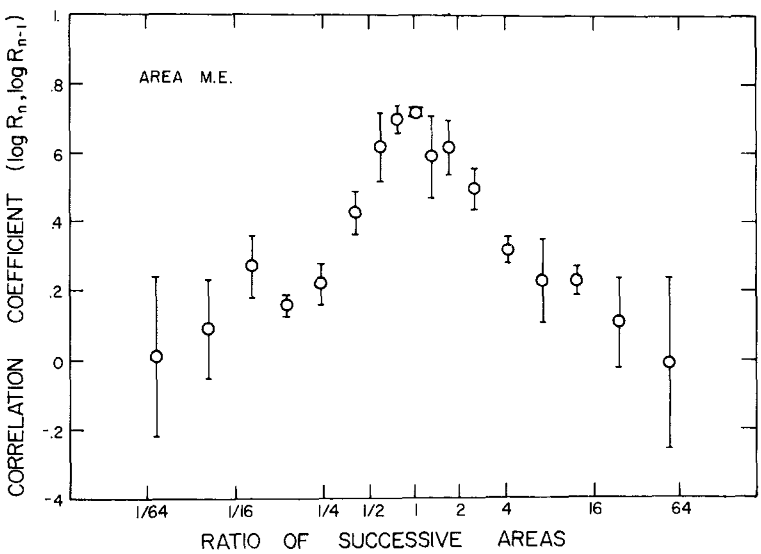

Figure 10. Correlation coefficient between the logarithm of responses on trial n and $n - 1$ as a function of the ratio of successive areas. (A separate correlation was determined for each stimulus pair (S_n, S_{n-1}) and then averaged across the same stimulus ratio. The circles represent the mean correlation over three subjects; the vertical bars enclose plus and minus one standard deviation based on the three independent means. M.E. = magnitude estimation.)

trials) were entered into the calculation of a single correlation coefficient, the correlation would be artifactually high because the absolute value of the response pairs would vary enormously across the stimulus range.

The correlation results are presented in

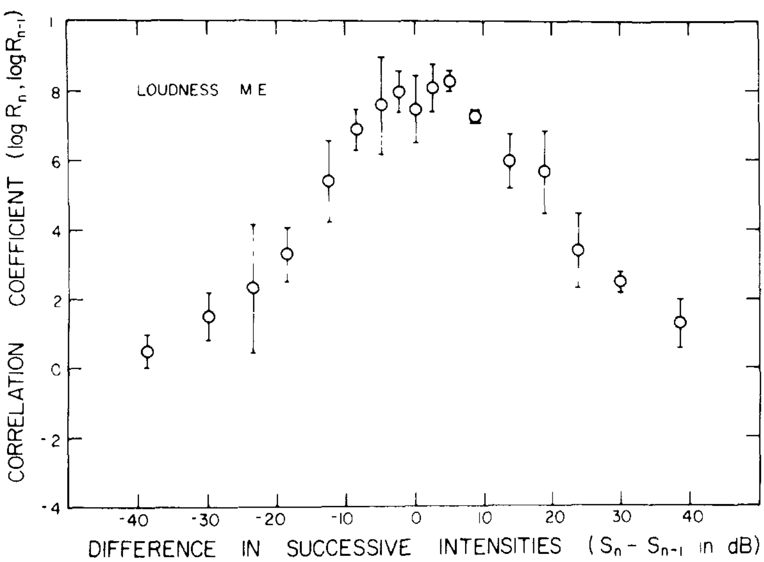

Figure 11. Correlation coefficient between the logarithm of responses on trial n and $n - 1$ as a function of the logarithmic difference in sound intensity (SPL) on trial n and $n - 1$. (A separate correlation was determined for each stimulus pair [S_n,S_{n-1}] and then averaged across the same stimulus separation. The circles represent the mean correlation over three subjects; the vertical bars enclose plus and minus one standard deviation based on the independent means. M.E. = magnitude estimation.)

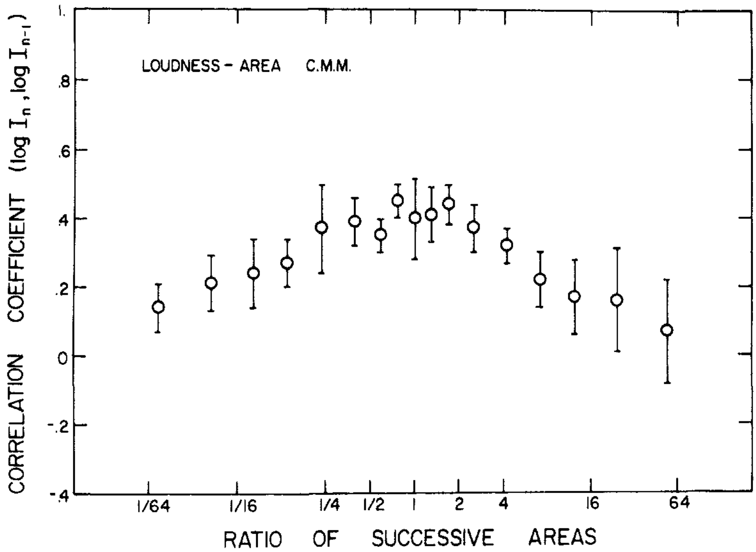

Figure 12. Correlation coefficient between the logarithm of intensity settings on trial n and $n - 1$ as a function of the ratio of successive stimulus areas. (A separate correlation was determined for each stimulus pair $[S_n, S_{n-1}]$ and then averaged across the same stimulus ratio. The circles represent the mean correlation over three subjects; the vertical bars enclose plus and minus one standard deviation based on the independent means. C.M.M. = cross-modality matching.)

Figures 10, 11, and 12 in which the vertical bars enclose the standard deviation of the points for the three subjects. The inverted V is clear for all three types of judgments, but not to an equal degree. The ME results are the most pronounced and agree substantially with previous findings for loudness. As far as we know, the results in Figure 10 for visual area represent the only available correlation data for this continuum. The most interesting result, because it is somewhat at odds with expectations, is shown in Figure 12 for CMM. Although the inverted V is present, it is considerably attenuated with a maximum correlation approximately half the size found for ME.

The inverted V was recently reported by Ward (1979) for the matching of time duration to the separation between two dots (presented visually), but an exact comparison of the quantitative details of the two studies is difficult because of procedural differences. Nonetheless, it appears that the inverted V does occur with CMM, but that the peak of the function is much reduced over that present for ME.

The fact that for successive signals of nearly the same intensity, the CMM correlation is peaked (much as in ME and MP, although somewhat attenuated) invites speculation about possible relations to the V pattern of relative variability in ME and MP. As far as we know, neither phenomenon directly implies the other. The fact that both are seen in ME and MP but only the peaked correlation is seen in CMM strongly suggests some independence of the two processes; however, the similar dependence on signal separation suggests that there may be some common element.

One possibility is suggested by physiological observations, as has been noted earlier (Luce & Green, 1978). Single-unit recordings on the eighth (auditory) nerve of cats and monkeys show that individual peripheral neurons are either operating as if they had not been stimulated at all or at their maximum rates of firing, except for a band of intensities that is about 15–20 dB wide. This band of intermediate activity forms a function of frequency that is roughly an asymmetric V, with the right limb considerably steeper than the left. These are called tuning curves (Galambos & Davis, 1943). Psychophysical analogues have been seen in human beings (Zwicker, 1974). This means, among other things, that two signals of the same frequency separated by more than 20 dB must code intensity through somewhat different fibers. For signals less than 20 dB apart, the critical information may be carried by the same fiber, and the activation of the same fibers may be the factor common to the two phenomena, at least for loudness.

It is less clear that any such simple mechanism mediates the results for visual area. Certainly, the mechanism is not peripheral, if it exists at all. Indeed, the fact that the correlations of successive responses peak and the relative variability of their ratio dips at small signal differences is very widespread in ME and MP—we know of no exceptions—casts some doubt on any attempt to treat them as primarily stimulus based. The more likely assumption is some sort of response mechanism that is used whenever observers are in ME and MP procedures and is in some way affected by the closeness of the signals. However, no one has yet postulated a specific response mechanism that accounts for these phenomena and that is sufficiently detailed to be tested. Berliner, Durlach, and Braida (1978) have discussed a model in which there are several "anchor" points, and the variability of a response depends upon how far the signal is from the nearest anchor. To the best of our knowledge, this provides no explanation of the correlation data.

In summary, (a) both the mean responses for ME and for CMM can be roughly described by power functions. (b) The interlocking of the exponents is reasonably consistent, more so when results from MP are used to predict CMM than when results from ME are used. (c) The coefficient of variation shows the familiar V-shaped pattern for ME of both visual area and loudness across separations in stimulus intensity on successive trials; but a ragged, flat function is obtained for CMM, and the absolute level of variability is higher by nearly an order of magnitude. (d) The correlation pattern is in the shape of an inverted V across separations in stimulus intensity on successive trials for all three types of judgments, but is attenuated for CMM. These are the major results one must consider in modeling the processes underlying psychophysical judgments of stimulus ratios. Perhaps the most important contribution of the present study to this enterprise is the finding that the V pattern describing the coefficient of variation is not a necessary consequence of the inverted-V correlation pattern. Such a linkage has been suggested in some of our earlier theorizing about magnitude estimation (Luce & Green, 1978). It seems premature to decide whether this disengagement of the V patterns is of general relevance to all forms of ratio estimation or is limited to CMM. We are currently developing theoretical models to further an understanding of these and related findings.

Reference Note

1. Luce, R. D., Baird, J. C., Green, D. M., & Smith, A. F. *Two classes of models for magnitude estimation.* Manuscript submitted for publication, 1980.

References

Baird, J. C. *Psychophysical analysis of visual space.* Oxford, England: Pergamon Press, 1970.

Baird, J. C., & Noma, E. *Fundamentals of scaling and psychophysics.* New York: Wiley, 1978.

Baird, J. C., Kreindler, M., & Jones, K. Generation of multiple ratio scales with a fixed stimulus attribute. *Perception & Psychophysics*, 1971, *9*, 399–403.

Berliner, J. E., Durlach, N. I., & Braida, L. D. Intensity perception, IX: Effect of a fixed standard on resolution in identification. *Journal of the Acoustical Society of America*, 1978, *64*, 687–689.

Galambos, R., & Davis, H. The response of single auditory nerve fibers to acoustic stimulation. *Journal of Neurophysiology*, 1943, *6*, 39–57.

Green, D. M., & Luce, R. D. Variability of magnitude estimates: A timing theory analysis. *Perception & Psychophysics*, 1974, *15*, 291–300.

Green, D. M., Luce, R. D., & Duncan, J. E. Variability and sequential effects in magnitude production and estimation of auditory intensity. *Perception & Psychophysics*, 1977, *22*, 450–456.

Jesteadt, W., Luce, R. D., & Green, D. M. Sequential effects in judgments of loudness. *Journal of Experimental Psychology: Human Perception and Performance*, 1977, *3*, 92–104.

Luce, R. D., & Green, D. M. The response ratio hypothesis for magnitude estimation. *Journal of Mathematical Psychology*, 1974, *11*, 1–14.

Luce, R. D., & Green, D. M. Two tests of a neural attention hypothesis for auditory psychophysics. *Perception & Psychophysics*, 1978, *23*, 353–371.

Mashhour, M. *Psychophysical relations in the perception of velocity.* Stockholm, Sweden: Almqvist & Wiksell, 1964.

Painton, S. W., Cullinan, W. L., & Mencke, E. O. Individual pitch functions and pitch-duration cross-dimensional matching. *Perception & Psychophysics*, 1977, *21*, 469–476.

Stevens, S. S. *Psychophysics: Introduction to its perceptual, neural and social prospects.* New York: Wiley, 1975.

Teghtsoonian, M. The judgment of size. *American Journal of Psychology*, 1965, *78*, 392–402.

Ward, L. M. Repeated magnitude estimations with a variable standard: Sequential effects and other properties. *Perception & Psychophysics*, 1973, *14*, 193–200.

Ward, L. M. Sequential dependencies and response range in cross-modality matches of duration to loudness. *Perception & Psychophysics*, 1975, *18*, 217–223.

Ward, L. M. Stimulus information and sequential dependencies in magnitude estimation and cross-modality matching. *Journal of Experimental Psychology: Human Perception and Performance*, 1979, *5*, 444–459.

Zwicker, E. On the psychoacoustical equivalence of tuning curves. In E. Zwicker & E. Terhardt (Eds.), *Facts and models of hearing*. Berlin, West Germany: Springer-Verlag, 1974.

Received May 8, 1979 ■