Chapter 3
Law of Additivity

3.1 Definition and Consistency with Ratio Scaling

According to the Law of Additivity, sensation magnitudes and other subjective magnitudes sum linearly when processed independently up to the stage of summation. The law may be regarded as established for most same-modality sensation magnitudes but not heteromodality ones. Because it may be applied to the generation of functions that relate subjective magnitudes to their underlying stimulus magnitudes, it is often used for proving the Power Law, as is done in Chap. 1. The procedure consists preferentially of presenting two subjectively equal magnitudes and assigning to their sum a numeral that indicates magnitude doubling. For example, if the numeral 1 is assigned to the component magnitudes, the numeral 2 would be assigned to their sum.

The concept of additivity of subjective magnitudes was introduced at least as early as 1920s by communication engineers for the purpose of determining the growth of loudness as a function of tone intensity. Finding that loudness growth with sound intensity was not well predicted by Fechner's Law, Fletcher and his associates at Bell-Telephone Laboratories searched for empirical methods that could determine it (Fletcher, 1929). Intuition told them that a tone delivered to both ears should sound twice as loud as a tone delivered to one ear alone. Their intuition seemed to be confirmed by subjective impression – a tone presented binaurally did seem to sound twice as loud as a monaural tone at the same physical intensity (Fletcher and Munson, 1933). As a further step, they increased the intensity of the monaural tone to make its loudness match the loudness of the binaural one. In this way, they were able to find the intensity ratio corresponding to doubling of loudness. By continuing the procedure, they were able to construct the function relating loudness to sound intensity. To validate the procedure, Fletcher (1935) presented simultaneously two tones of equal loudness but different frequencies to the same ear and compared the resulting loudness to the loudness of the single tone. As long as the frequency separation was sufficient to prevent a destructive interaction, the two tones seemed to be twice as loud as a single tone. By matching consecutively the loudness of the

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component tones and that of their sum to a third tone, Fletcher found roughly the same relationship between loudness and sound intensity as in the binaural experiment. Fletcher and Munson extended the monaural procedure to multiple tones and further confirmed the relationship between the two variables obtained initially.

In the same time period, other investigators used more direct procedures to obtain loudness scales. Observers were requested to adjust the loudness of one tone to make it twice or half as loud as that of another tone. Other loudness ratios were used as well. In some experiments, the observers were required to judge the loudness ratios between tones of preset intensity. According to Stevens and Davis's (1938) review, through their agreement, these more direct procedures, although less precise, validated the procedures based on summation. The relationships for half loudness and 0.1 loudness are shown graphically in Fig. 3.1. They are expressed in terms of intensity levels producing loudness equality. The agreement among the various experiments based on direct fractionation and between them and summation experiments is rather impressive, especially for loudness halving. It may be regarded as an early validation of the Law of Additivity.

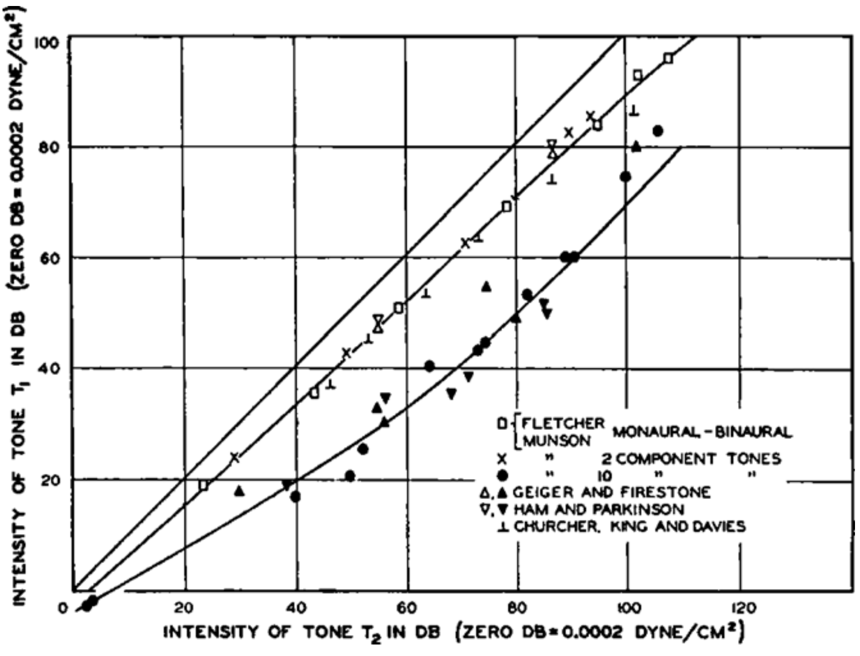

Fig. 3.1 The ordinate shows the SPL of a tone that appears half as loud as the same tone at a SPL indicated by the abscissa (unfilled triangles and inverted T symbols) or one tenth as loud (filled triangles). The unfilled squares show the SPLs of a tone presented binaurally (ordinate) and monaurally (abscissa) for loudness equality. The slanted crosses and filled circle show the SPLs of two-component, respectively, ten-component sounds (ordinate) that sound equally loud as one-component sounds. Reproduced from Stevens and Davis (1938), with permission from the American Institute of Physics

3.2 Further Validation of the Law for Loudness

Loudness appears to have been the preferred modality for experiments on the additivity of subjective magnitudes. Many concerned the loudness of binaural tones, as exemplified by the early experiments described in the preceding section. Perhaps the most fundamental ones were dedicated to proving that the loudness magnitude of a tone heard binaurally is, indeed, equal to twice the loudness magnitude of the same tone heard monaurally; stated more generally, that the monaural loudness magnitudes are interaurally additive.

One experimental series utilized a binaural loudness function established by several methods that produced mutually consistent results (Hellman and Zwislocki, 1963). The results, indicated by the various symbols in Fig. 3.2, refer to loudness ratios rather than to absolute loudness magnitudes. Nevertheless, they are anchored

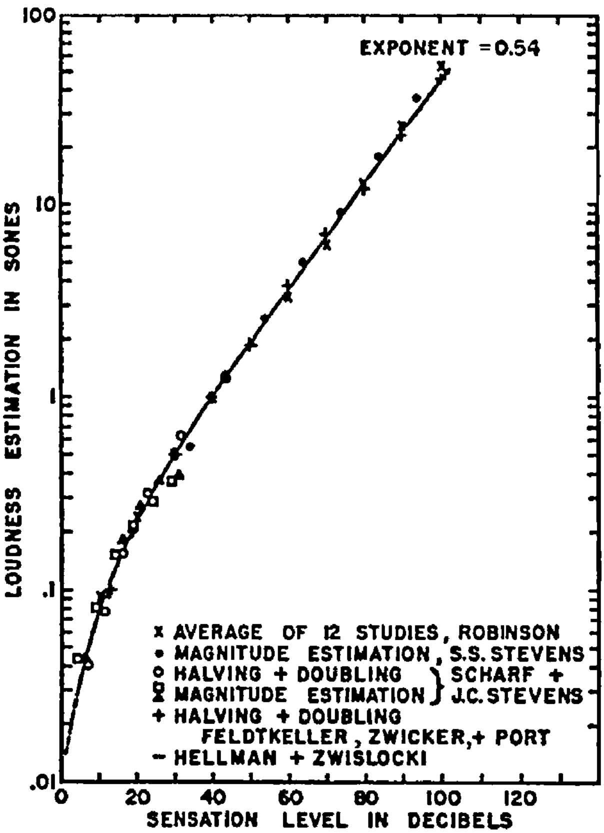

Fig. 3.2 Binaural loudness curve obtained by magnitude estimation with a reference standard consistent with AME. The various symbols refer to loudness ratios determined by a number of investigators using various methods. Reproduced from Hellman and Zwislocki (1963), with permission from the American Institute of Physics

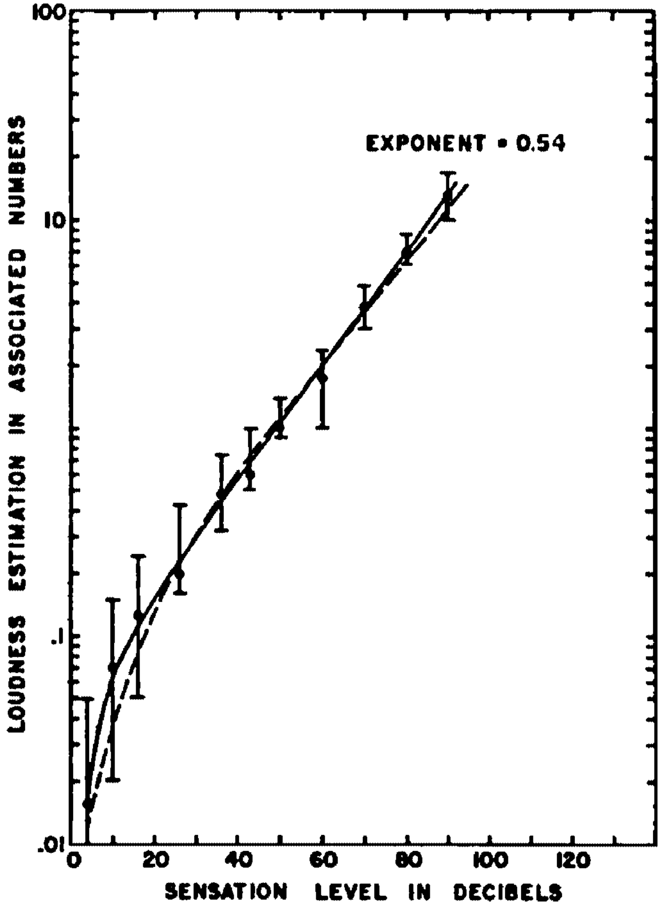

Fig. 3.3 The solid line indicates the monaural loudness curve obtained on nine observers by AME. The solid circles and vertical lines refer to geometric means and standard deviations of the group. The intermittent curve has been reproduced from Fig. 3.2. Reproduced from Hellman and Zwislocki (1963), with permission from the American Institute of Physics

on the solid curve based on reference standards consistent with such magnitudes (Hellman and Zwislocki, 1961; also Chap. 1). Corresponding monaural loudness curves were determined by two methods. One similar to the method with the reference standards, used in the binaural experiments, the other based on absolute magnitude estimations without a reference standard (Hellman and Zwislocki, 1963). Both curves are shown in Fig. 3.3, the first by means of the intermittent line, the second by means of the solid one. The group means and standard deviations for the latter are also given. Both the binaural curve of Fig. 3.2 and the monaural curves of Fig. 3.3 are reproduced in Fig. 3.4. To the binaural curve obtained with designated standards and indicated by the intermittent line is added a theoretical curve corresponding to the monaural curve obtained without designated standards. This is done

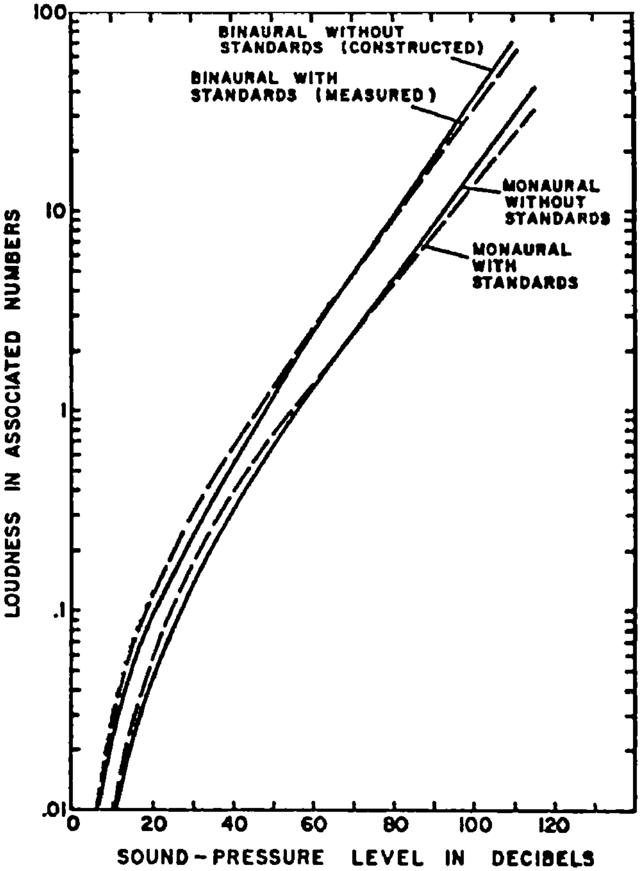

Fig. 3.4 Solid lines refer to binaural and monaural loudness curves, respectively, obtained by magnitude balance and derived from the curves of Figs. 3.2 and 3.3. Intermittent lines correspond to loudness curves determined with reference standards. Reproduced from Hellman and Zwislocki (1963), with permission from the American Institute of Physics

on the assumption that designated standards have the same effect in terms of loudness ratios on the binaural curve as on the monaural one. The reader should note that the loudness ratio between the corresponding binaural and monaural curves remains roughly the same over the whole extent of the curves, even where the curves become steeper near the threshold of detectability. It amounts approximately to loudness doubling and indicates a linear process of summation.

A more detailed analysis of binaural loudness summation indicates, however, that there are slight sensitivity differences between the two ears, so that the loudness of a binaural sound should not be expected to be exactly twice the loudness experienced in anyone of the two ears. Rather, it should be twice the loudness averaged between them. According to Shaw et al. (1947) the average interaural threshold difference amounts to 3.8 dB, roughly, 4 dB. According to Hellman and Zwislocki (1961), the

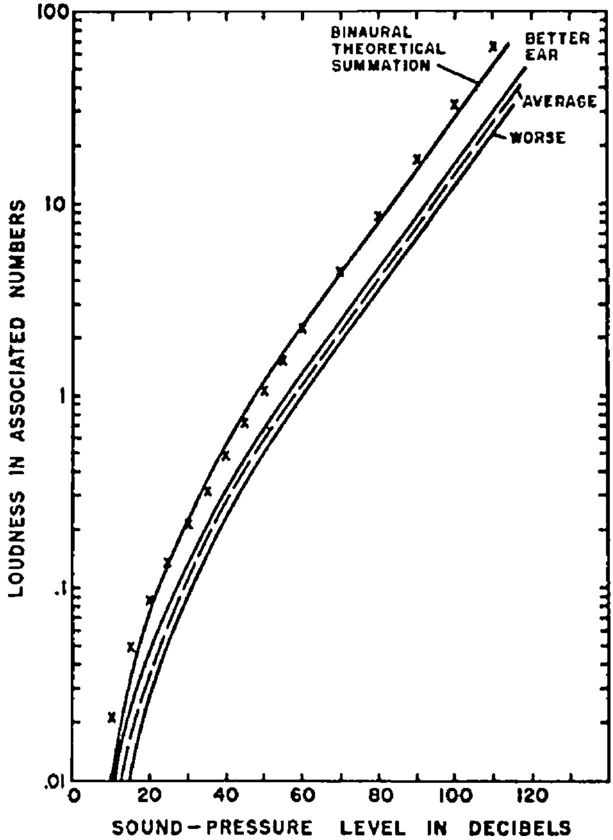

Fig. 3.5 The pair of lower lines bisected by the intermittent line indicate monaural loudness curves spaced by the average interaural sensitivity difference; the upper solid line indicates their theoretical summation. The crosses indicate the empirical binaural loudness values. Reproduced from Hellman and Zwislocki (1963), with permission from the American Institute of Physics

difference is preserved at suprathreshold levels. The relationship is illustrated in Fig. 3.5. The monaural loudness curves, spaced by 4 dB along the sound-pressure axis are shown by the thin curves; the intermittent line shows their SPL average. The ordinates of the thick curve are equal to the sums of the ordinates of the monaural curves. The crosses indicate the empirical loudness magnitudes derived from Fig. 3.2 through appropriate conversion of SLs to SPLs. The agreement between the numerical values obtained by the theoretical summation and the empirical values demonstrates binaural additivity of monaural loudness magnitudes.

The additivity was further confirmed by comparing the results shown in Fig. 3.5 to the results obtained in the past by Fletcher and Munson (1933) who determined pairs of SPLs producing loudness equality between monaurally and binaurally presented tones. To obtain corresponding SPLs from Fig. 3.5, horizontal cuts were made through the family of curves of the figure. The average SPLs so determined

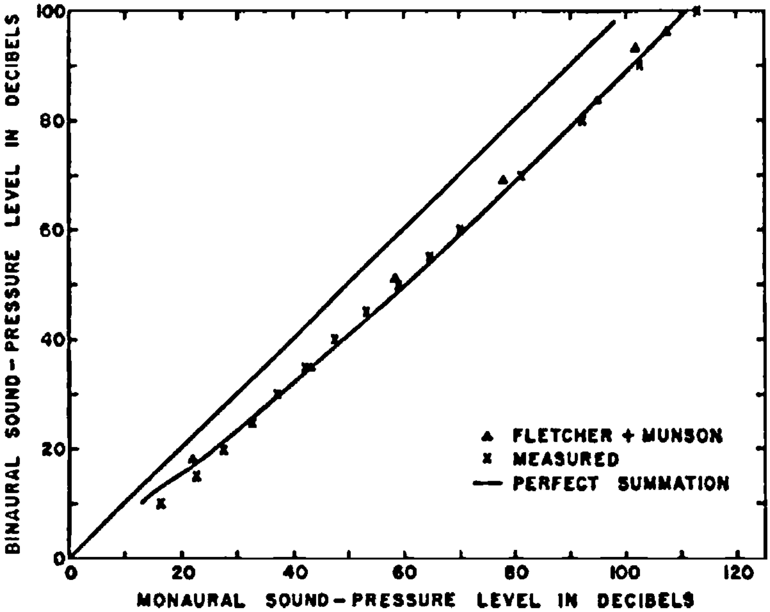

Fig. 3.6 Binaural SPL versus monaural SPL for loudness equality. The lower solid line was obtained by sectioning horizontally the mean monaural and binaural curves of Fig. 3.5; the values marked by slanted crosses were derived in an analogous fashion from the empirical values marked by slanted crosses in the same figure; the values marked by filled triangles were obtained empirically by Fletcher and Munson in 1933. The upper solid line marks perfect interaural symmetry. Reproduced from Hellman and Zwislocki (1963), with permission from the American Institute of Physics

for the monaural tones were plotted as abscissas of the solid curve in Fig. 3.6, the SPLs of the equally loud binaural tones, as its ordinates. The empirical pairs of SPL were derived from Fig. 3.5 in a similar fashion and are marked by slanted crosses. The numerical values of Fletcher and Munson are marked by filled triangles. They lie close to the values obtained by Hellman and Zwislocki (1963).

Perhaps the most direct confirmation of binaural additivity of monaural tones was obtained by Marks (1978) who measured the loudness of binaural and monaural tones on the same observers by the method of magnitude estimation with reference standards chosen by the observers themselves. As already mentioned, the method is closely related to the AME method. The measurements were performed at three sound frequencies – 100, 400 and 1,000 Hz, and involved interaurally unequal loudness magnitudes in addition to the equal ones. Specifically, the binaural loudness was measured as a function of SPL in one ear while the SPL in the contralateral ear was kept constant at several levels. The procedure was expected to produce loudness increments independent of the total loudness in the presence of binaural loudness additivity. Graphically, it was expected to generate families of parallel loudness curves spaced by loudness steps corresponding to the SPL steps. Examples of such

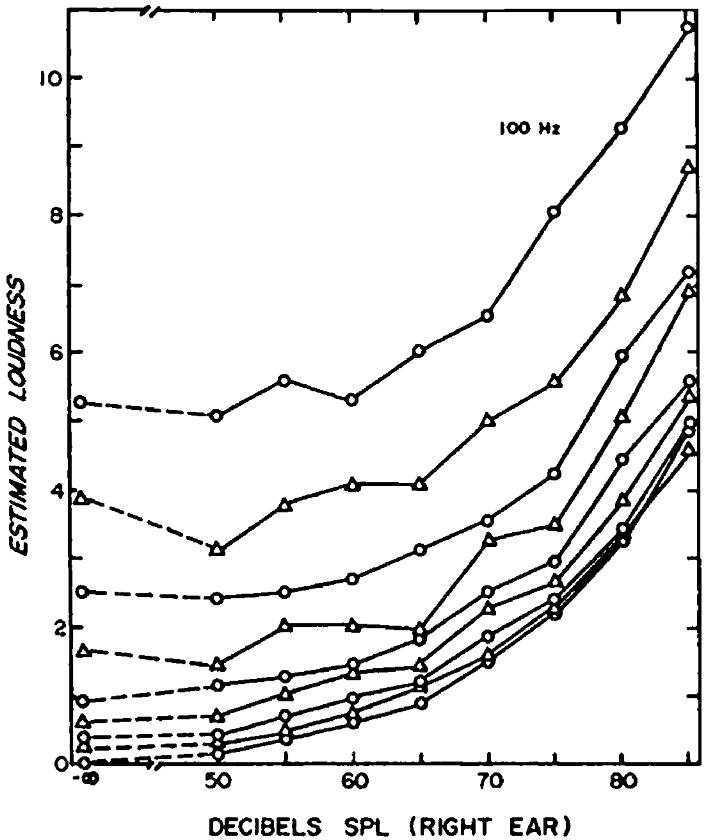

Fig. 3.7 Magnitude-estimation curves of binaural loudness summation of interaurally unequally loud tones of 100 Hz. The curves go through geometric means of group values and are plotted on a linear ordinate scale over the abscissa scale in decibels, referring to the right ear. The SPL difference between the two ears was varied parametrically. Reproduced from Marks (1978), with permission from the American Institute of Physics

families obtained on partially overlapping groups of 14 observers each are shown in Figs. 3.7 and 3.8, the former for the sound frequency of 100 Hz, the latter for that of 1,000 Hz. The curves, which follow the geometric means of the individual loudness estimates, are roughly parallel, as they should be in the presence of loudness additivity. They follow approximately power functions and would appear as straight lines on double-logarithmic coordinates. This is shown in Fig. 3.9 for a subset of the data limited to equally loud sounds in both ears. The circles and squares refer to monaural loudness magnitudes in the left and right ears, respectively, the triangles, to the corresponding binaural magnitudes. All 3 sound frequencies – 100, 400 and 1,000 Hz, are included, and the functions have power exponents of approximately 0.6 for the higher frequencies and 0.75, for the lowest, in rough agreement with the results obtained previously by absolute magnitude-balance (e.g. Hellman and Zwislocki,

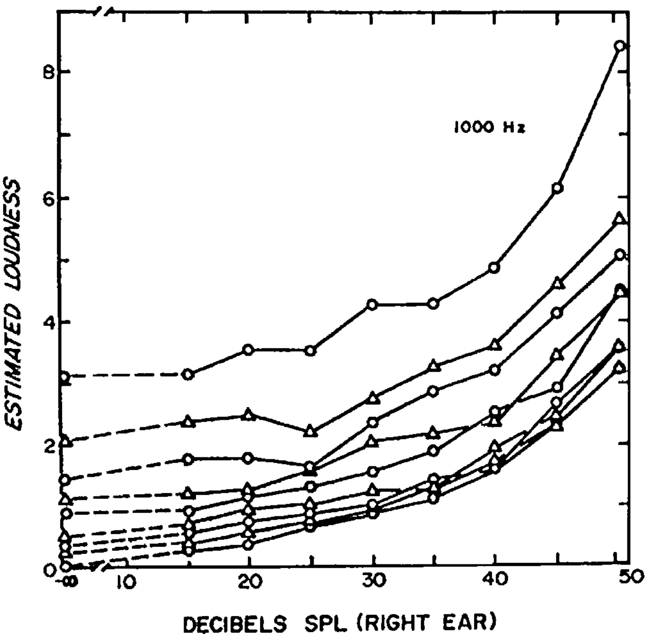

Fig. 3.8 Same as Fig. 3.7 for 1,000 Hz. Reproduced with permission from the American Institute of Physics

1968). Note that, in agreement with the latter, the 100-Hz curves are slightly concave downwards. The ordinates of the binaural curves are approximately twice the ordinates of the monaural curves for all three frequencies, indicating loudness doubling in conformity with the earlier results of Hellman and Zwislocki (1963).

Both studies, that of Hellman and Zwislocki and that of Marks indicate binaural loudness additivity. Such additivity was already assumed by Fletcher and Munson (1933) for the purpose of generating loudness functions and was validated by the agreement of their results with those produced by magnitude balance, as shown in Fig. 3.6 (Hellman and Zwislocki, 1963), and magnitude estimation (Marks, 1978). Binaural loudness additivity was also found by Levelt et al. (1972) who compared the loudness in the two ears by the method of paired comparisons and analyzed their results with the help of the theory of conjoint measurement (Luce and Tukey, 1964).

Binaural loudness additivity consistent with loudness growth according to a power function having an exponent of about 0.6 was not found by all experimenters. Caussé and Chavasse (1942) found a difference of only 6 instead of 10 dB for loudness equality between binaural and monaural tones at medium SLs. Interestingly, they found a difference of 3 dB at low SLs, which is consistent with loudness additivity in the presence of a linear loudness growth (e.g. Hellman and Zwislocki, 1963, 1968; see Chap. 2). The less than perfect summation at higher SLs may have been due to asymmetrical loudness matching in which only the monaural tone intensity was varied (Hellman and Zwislocki, 1963). An incomplete summation seems to

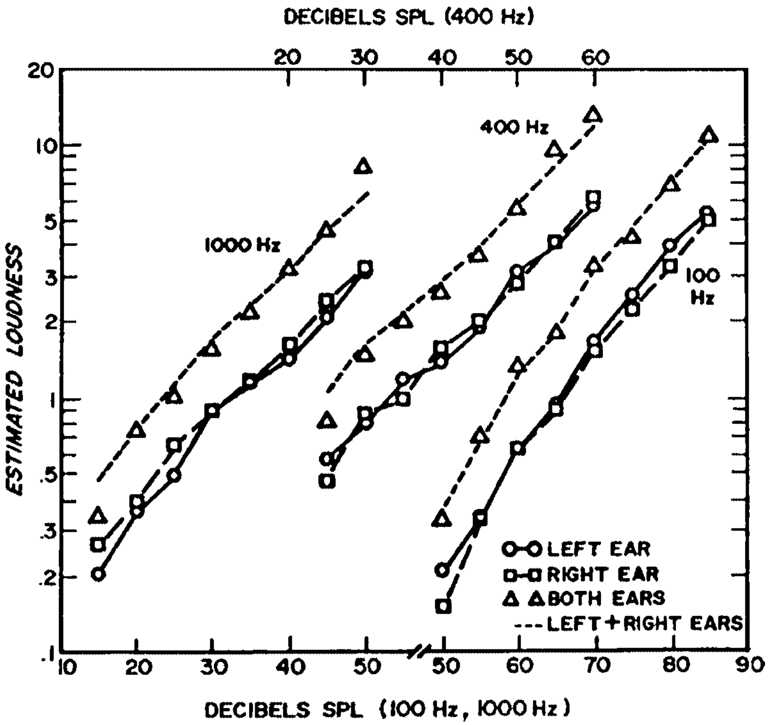

Fig. 3.9 Data of Figs. 3.7 and 3.8 with added data for 400 Hz are plotted on log. ordinate scale for interaural loudness equality. Reproduced from Marks (1978), with permission from the American Institute of Physics

have been obtained also by Scharf and Fishkin (1970) in spite of the fact that they used magnitude estimation and production procedures. These procedures are not always bias free, however, unless precautions mentioned in Chap. 1 are observed, especially, when relative rather than absolute loudness estimates are made. According to Sharf and Fishkin, binaural loudness was equal on the average to 1.7 the monaural loudness rather than 2. The less than perfect apparent summation may have been due to an artifactually reduced slope of their loudness function, which obeyed an exponent of 0.5 rather than 0.6. When the exponent is corrected by multiplication to 0.6, a perfect loudness summation is obtained (Marks, 1978). In general, lack of perfect binaural loudness summation seems to have occurred in studies in which an experimental bias of one sort or other could be demonstrated. Studies consistent with the best established course of the loudness functions appear to indicate binaural additivity.

Marks et al. (1991) were able to show that binaural summation remains unaffected when the tones in the two ears are not at exactly the same sound frequency. They presented simultaneous dichotic pairs of 1-s tone bursts at the frequency of 1,000 Hz in one ear and of 1,000, 1,040, and 1,080 Hz in the other, as well as

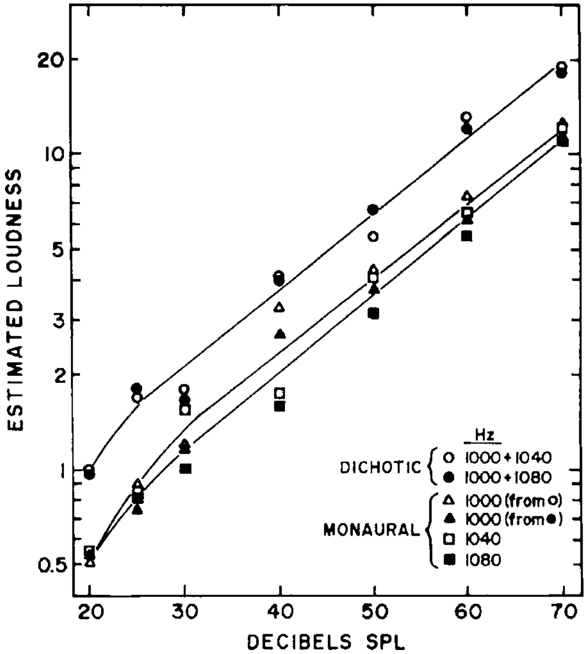

Fig. 3.10 Binaural loudness summation of equally loud simultaneous tones at slightly different sound frequencies, determined by magnitude estimation. The circles refer to binaural tone pairs, the remaining symbols, to the monaural tones. Reproduced from Marks et al. (1991), with permission from the Psychonomic Society

monotic tone bursts at the same frequencies. The tones were presented at 7 SPLs between 20 and 70 dB. The 16 observers participating in the experiments judged the loudness magnitudes of the tone bursts by the method of magnitude estimation relative to reference standards chosen by themselves. The experiments were counterbalanced by rotating the earphones between the two ears. The group results are displayed in Fig. 3.10 on logarithmic coordinates. The geometric means of the magnitude estimates are indicated by the various symbols and interpolated by solid lines. One line was sufficient for all the dichotic results, two parallel once were needed for the monotic results referring to different frequency combinations. Above an SPL of 30 dB, all the lines are straight indicating loudness growth according to power functions. Along the SPL axis the space between the dichotic and monotic curves amounts to about 10 dB, which would mean loudness doubling if the slope of the lines conformed with a power exponent of 0.6, expected for unbiased loudness functions. In fact, the curves follow an exponent of only 0.5, probably due to a bias caused by the lack of experience of the majority of the observers with loudness scaling. The exponent of 0.5 in combination with a horizontal spacing of 10 dB is consistent with a binaural/monaural loudness ratio of 1.7, similar to that obtained by Scharf and Fishken. When the exponent is corrected to 0.6, in agreement with the exponent prevailing for loudness functions that result when great care is taken to avoid biases, perfect binaural loudness summation is obtained.

Perhaps the greatest significance of the experiments of Marks, Algom and Benoit lies in the finding that perfect (after exponent correction) binaural loudness summation is maintained even for tones that are not identical in sound frequency and, therefore, in pitch. Thus, loudness and pitch must constitute separate, noninteracting attributes of sound. Experiments described below further strengthen this notion.

Already Fletcher (1935) used pairs of simultaneous, monaural tones of different sound frequencies to study the summation of their loudness magnitudes. He found that the summation was equivalent to binaural summation of tones of the same sound frequency as long as the frequency separation between them was sufficient. His results were later confirmed by those of Zwicker et al. (1957) who used multiple tone complexes. The loudness of the complexes increased with the frequency separation of the components, presumably because of decreasing mutual interaction.

As variants of Fletcher's procedure, experiments were performed in which the component tones were not presented simultaneously but separated by various time intervals. In one set of experiments, triads of 10-msec tone bursts having different sound frequencies were presented monaurally to seven observers (Zwislocki et al., 1974). The time interval between the first two bursts was variable, that between the second and third bursts was kept constant at 500 msec. The observers had to adjust the loudness of the third burst to match the combined loudness of the first two bursts or to the loudness of the second burst alone. The purpose of the latter, auxiliary, procedure was to determine the effect of the first burst on the loudness of the second. In the first and second sequences, the first burst was at a sound frequency of 1 kHz and the second at that of 4 kHz. The third burst was at 2 kHz, the geometric mean of 1 and 4 kHz, in the first sequence and at 4 kHz in the second and third ones. In the third sequence, all the bursts were at the same sound frequency of 4 kHz. As shown in Fig. 3.11, independent of sound frequency, the first burst had only a negligible effect on the loudness of the second. The combined loudness magnitude of the first

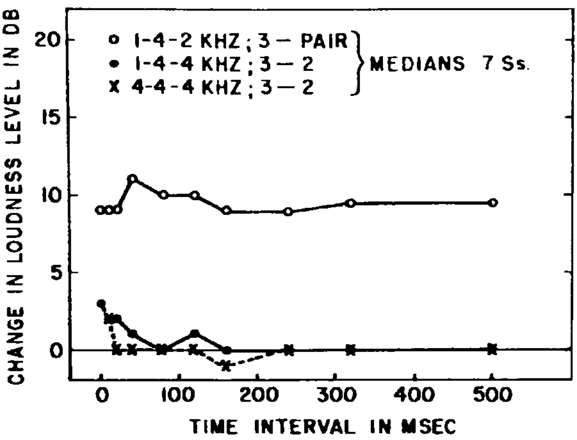

Fig. 3.11 Loudness summation of two tone bursts at two different frequencies (1,000 and 4,000 Hz) separated by a time interval of 500 msec. A third burst at 4,000 Hz or 2,000 Hz was compared in loudness either to the tone pair or to the second burst in the pair. The data points and interpolating curves refer to corresponding loudness levels. Reproduced from Zwislocki et al. (1974), with permission from the Psychonomic Society

and second bursts having the sound frequencies of 1 and 4 kHz, respectively, was equal to the linear sum of their loudness magnitudes, as judged from the loudness-level difference of approximately 10 dB. The loudness integration spanned a time interval of at least 500 msec. Apparently, the loudness of the second burst was added linearly to the memorized loudness of the first.

In another set of experiments, described in Chap. 1 (Zwislocki, 1983), 20-msec tone bursts separated by 50-msec time intervals and having sound frequencies of 1 and 4 kHz, respectively, were presented monaurally with a repetition rate of 1 sec^{-1}. The 1-kHz bursts were presented at a number of SL, and the SLs of the 4-kHz bursts were adjusted so as to make the bursts, respectively, 0.5, 1.0, and 2.0 times as loud as the 1-kHz bursts. The loudness magnitudes of the component bursts and of the burst pairs were determined by the method of absolute magnitude balance. As described in Chap. 1, the loudness of the burst pairs proved to be approximately equal to the linear sum of the loudness magnitudes of the single bursts.

The two sets of experiments confirmed Fletcher's assumption that the loudness magnitudes of tone bursts of sufficiently different sound frequencies are additive. As an extension of this finding, they show that the process of addition can be extended over a considerable span of time. Together with the demonstration of binaural (diotic) and dichotic loudness additivity, the experiments demonstrate that the law of additivity of subjective magnitudes holds for loudness.

3.3 Generality

Experiments performed in other sense modalities indicate that additivity of sensation magnitudes is not limited to loudness but is a more general sensory phenomenon. However, it occurs only under specific conditions that may differ among the senses. Among the non-chemical senses, the conditions encountered in vibrotaction appear to be the most similar to those in hearing, those encountered in vision, the most dissimilar and the most restricted.

In the sense of touch, probably the most extensive quantitative experiments were performed on the glabrous skin of the hand by means of vibrators. They made it possible to study response characteristics paralleling those of hearing. For example, the threshold of vibration detectability was measured as a function of vibration frequency. On the basis of anatomy and, by varying the size of the vibrating contactor, Verrillo and his associates (e.g. Verrillo, 1968) were able to establish that the most sensitive vibration receptors were the Pacinian corpuscles, especially in the midfrequency range, around 250 Hz. Their sensitivity decreased toward both high and low frequencies. At low frequencies, other receptors, summarily called "Non-Pacinian" determined the vibrotactile threshold. The relationships are schematized in Fig. 3.12 according to the analysis of Bolanowski and his associates (e.g. Bolanowski et al., 1993). The finding signifies that, under appropriate conditions, the vibrotactile information is conveyed by Pacinian corpuscles at medium frequencies and by the

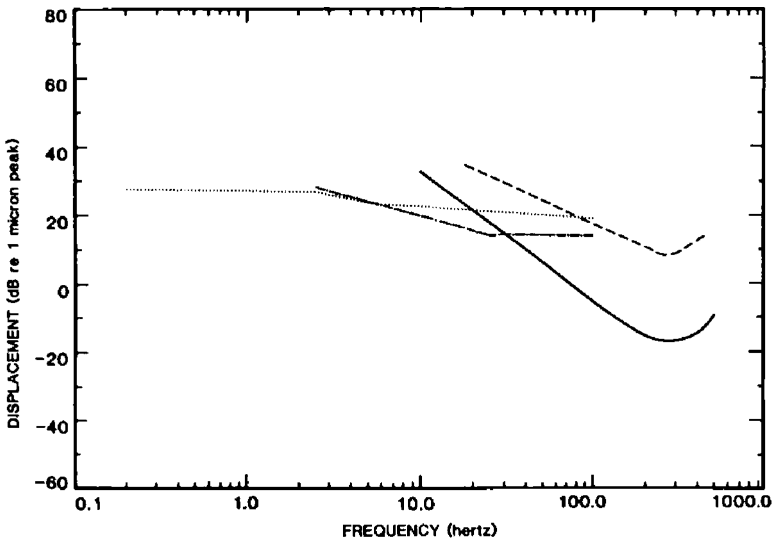

Fig. 3.12 Thresholds of detectability of Pacinian (continuous line) and three None Pacinian vibrotactile receptors. Reproduced from Bolanowski et al. (1993), with permission from Taylor & Francis Group, LLC

Non-Pacinian ones at low frequencies, indicating that the two processes are separated before the stage of their integration.

Exploiting the separation, Verrillo and Gesheider (1975) performed experiments on 5–6 observers, analogous to the auditory experiments of Zwislocki et al. (1974), in which two short bursts of sinusoids of different frequencies were followed by a third burst of intermediate frequency. The time interval between the first two bursts was varied between 35 and 500 msec, and the third burst followed the second burst at a time interval of 700 msec. The first burst was at a frequency of 300 Hz, the second at that of 25 Hz, and the third at that of 80 Hz. The observers had to set the first two bursts at equal subjective intensity, and adjust the third burst to match the total subjective magnitude of the first two bursts combined. The result is shown in Fig. 3.13 by the unfilled circles and the interpolating solid line. Unlike in hearing, the adjusted magnitude depends on the time interval between the first two bursts. At the shortest interval, it is equal to the arithmetic sum of the individual magnitudes of the two bursts, as indicated by an increment of 6 dB. Because the subjective vibrotactile magnitudes in the range of the experiments grew with vibration intensity according to a power function with an exponent of about 0.5, the 6-dB ratio amounts to magnitude doubling, indicating additivity. The magnitude decrement occurring with the increasing time interval between the stimulus bursts suggests an effect of decreasing memory.

For comparison purposes, the intermittent line in the figure shows what happens when the stimulus bursts are at similar vibration frequencies so that they are processed in the same Pacinian system before being integrated. The integration

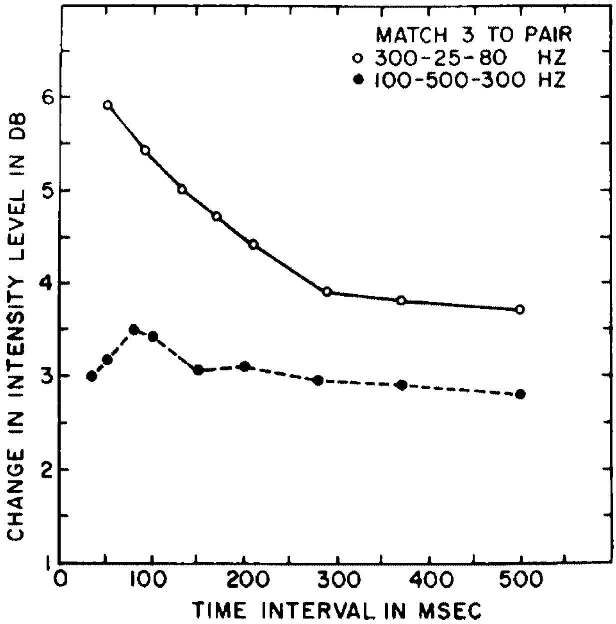

Fig. 3.13 Intensity level of a vibration burst at 80 Hz matched in subjective intensity to a preceding burst pair at 300 and 25 Hz respectively (unfilled circles) and the intensity level of a vibration burst at 300 Hz matched in subjective intensity to a preceding burst pair at 100 and 500 Hz respectively (filled circles). The abscissa scale refers to the inter-burst time interval in the pairs. Reproduced from Verrillo and Gesheider (1975), with permission from the Psychonomic Society

produces a magnitude increment of only 3 dB, corresponding approximately to the summation of stimulus energies rather than to the summation of the subjective magnitudes. This is not a trivial outcome because the bursts were not presented simultaneously so that their energies could not have been summated directly in the stimulus domain.

The subjective magnitude additivity was confirmed by Marks (1979) who used roughly the same experimental paradigm as he did for audition (Marks, 1978). A group of six subjects was involved. The stimuli consisted of 1-sec bursts of 250- and 20-Hz vibration, respectively, presented through a contactor with a contact area of 0.64 cm^2 singly and in combination. In one experiment, their intensities were arranged according to a 49 sensation-level matrix so that every stimulus component was presented at 7 different levels. Every observer judged the subjective magnitudes of the 2-frequency stimuli 6 times, and the results were expressed in terms of geometric means. The geometric means of the group results are shown in Fig. 3.14 as functions of SLs of the 250-Hz bursts. Every curve belongs to a different added 20-Hz tone burst with its SL marked at the curve. The parallel course of the curves indicates that the increments were added arithmetically.

In a supplemental experiment, the 250- and 20-Hz stimuli were presented singly as well as in matched pairs at 7 suprathreshold SLs. Their subjective intensities

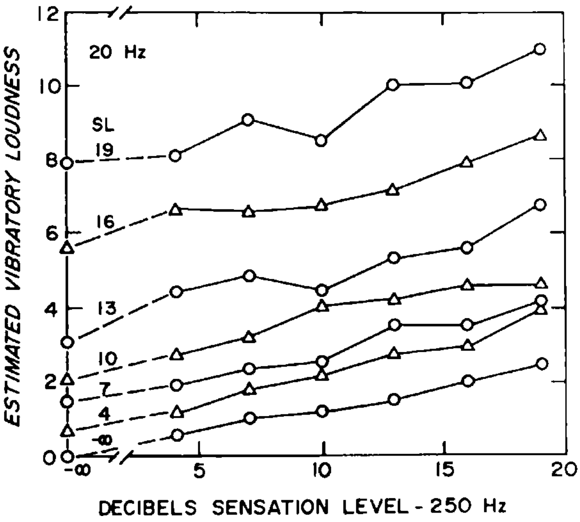

Fig. 3.14 Subjective intensity of pairs of simultaneous vibration bursts at 250 and 20 Hz, respectively, plotted on a linear scale over the sensation level of the 250-Hz burst. (From Marks, 1979, with permission granted from copyright holder)

were determined by magnitude estimation without designated reference standards. A group of four observers judged every stimulus four times. The geometric means of the group responses are shown in Fig. 3.15 by various symbols as functions of the respective stimulus levels. The magnitudes of the responses to the combined stimuli are plotted by triangles over the 250-Hz axis. For comparison, the upper intermittent line follows the arithmetic sums of the corresponding subjective magnitudes of the 250- and 20-Hz stimuli. The agreement between the empirical responses to the combined stimuli and the theoretical sums indicates that the observers summed the subjective magnitudes of the component stimuli linearly.

The results of the experiments of Verrillo and Gescheider and of Marks clearly show that the law of additivity applies to vibrotaction. Additional experiments would be required to see if it applies to the sense of touch more generally.

The visual system tends to average the brightness of visual stimuli rather than summating it. Thus far, brightness additivity was demonstrated in only one set of conditions, when both eyes were illuminated uniformly – the so-called "Ganz-feld" illumination, which is contourless. Bolanowski (1987), who discovered the phenomenon investigated it for binocular brightness equality. He found simply that in binocular illumination the light appeared twice as bright as in monocular one. Because, in monocular illumination, which he needed for comparison with the binocular one, the brightness of the light tends to fade out with time, he used short (1-s) light flashes, as did Barlow and Verrillo (1976) for the same reason when determining the Ganz-feld brightness function.

Like Barlow and Verrillo, Bolanowski produced a separate ganzfeld for each eye by back-illuminating half a ping-pong ball, trimmed carefully to fit snugly around the eye ball. He tested the fit by measuring the time required for the light to fade out when only one eye was illuminated. The uniformity of the illuminated field was achieved by mounting each half-ball at the end of a nonreflecting white

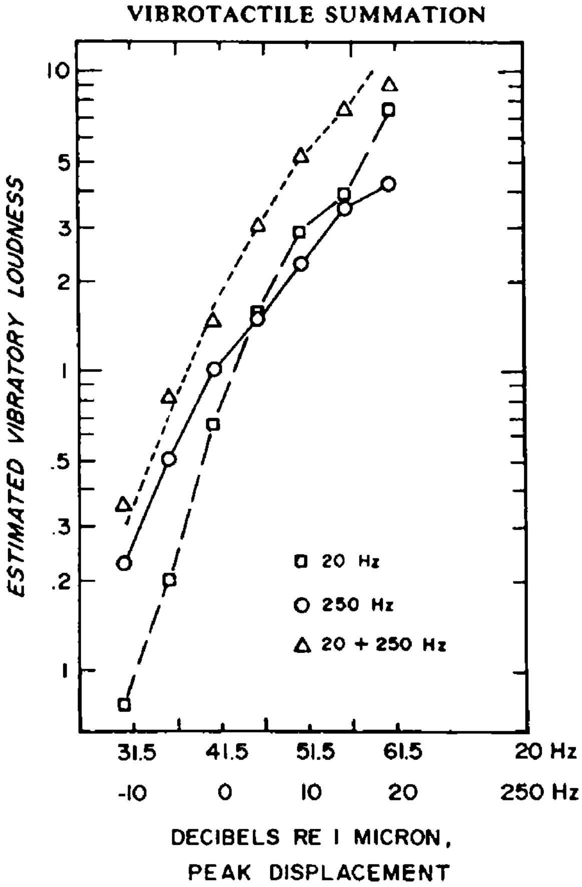

Fig. 3.15 Subjective intensity of single vibration bursts at 20 and 250 Hz and of pairs of the bursts, plotted on a logarithmic scale over peak displacement amplitudes of the vibrations. (From Marks, 1979, with permission granted from copyright holder)

cone. He used achromatic light produced by a halogen light source (Xenophot HLX64625) with appropriate optics. The light intensity was controlled by neutral-density filters and calibrated with an IL 700 Research Radiometer incorporating a CIE standard-observer curve correction. (0.0 Log I is equivalent to 3232 cd/m^2 in the figures). A group of 16 naive observers participated in the experiment. After appropriate training with estimating the lengths of lines, they had to estimate the light brightness according to the method of absolute magnitude estimation. They were dark-adapted for 20 min, and their thresholds were measured before the magnitude-estimation experiments. In the latter, light intensities were presented in a quasi-random order, except that the highest intensity was not presented before the lowest one to minimize light adaptation. A group of eight observers first received a monocular set of ganzfeld stimuli in the right eye, then, a corresponding set of binocular stimuli. For another group of eight observers, this order was reversed. Some observers received a monocular stimulus in the left eye as well to check on the interocular symmetry. Because the symmetry requirement was satisfied, only the right eye was used for monocular stimuli in the main experiment. Individual brightness

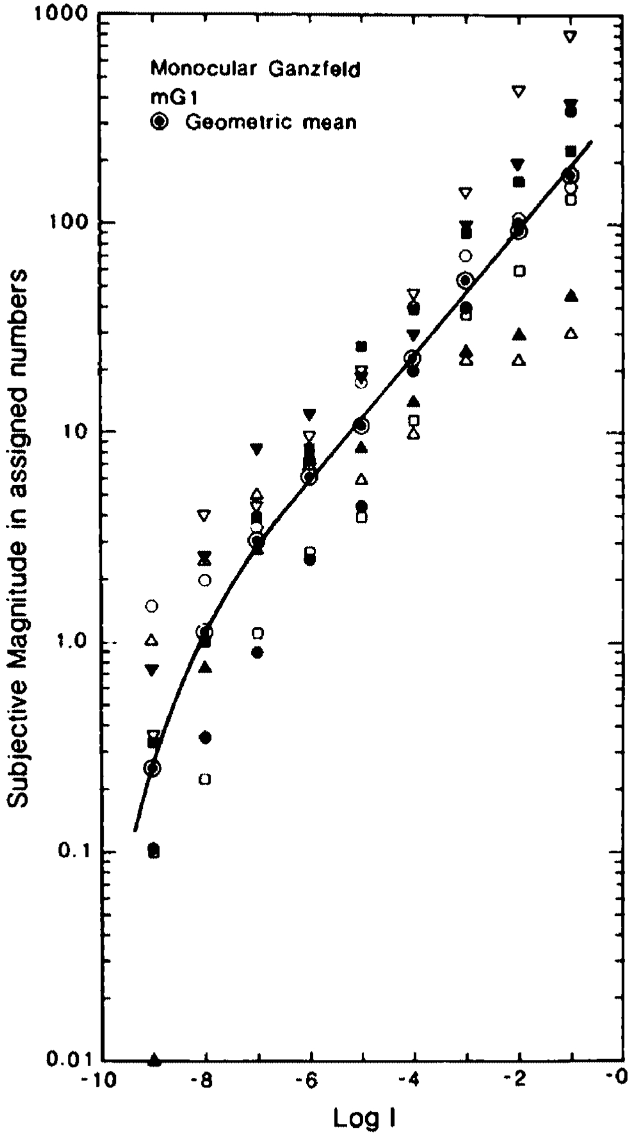

Fig. 3.16 Monocular brightness of achromatic ganzfeld light flashes determined by AME as a function of light intensity – individual data and geometric means. The curve has been fitted to the group means by eye. The abscissa scale is logarithmic and referred to $3{,}232\,\mathrm{cd/m^2}$. (Reprinted from Bolanowski, 1987, with permission from Elsevier)

estimates produced by the first group of observers, as well as their geometric means, are shown in Fig. 3.16 as functions of light intensity. The geometric means are interpolated by eye with the result indicated by the means of the solid curve. Above about -8 log units, the latter follows a power function with an exponent of about 0.29,

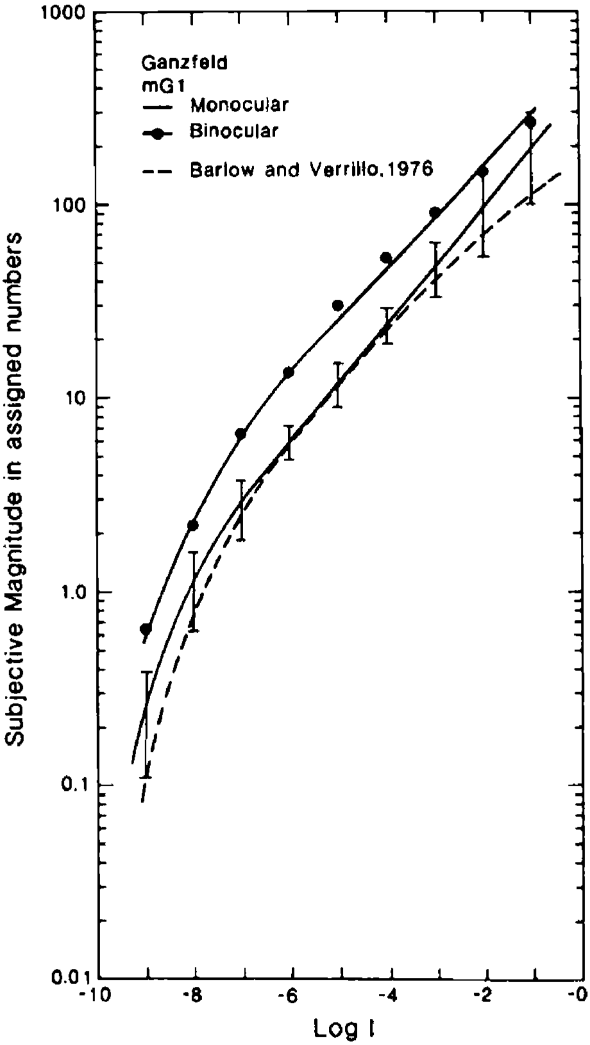

Fig. 3.17 Binocular brightness of achromatic ganzfeld light flashes determined by AME as a function of light intensity referred to $3,232\,\text{cd}/\text{m}^2$. Filled circles indicate the geometric group means; the solid line has been fitted to them by eye. The thin line indicates the monocular brightness reproduced from Fig. 3.16, and the vertical lines, the corresponding standard deviations of the individual data. For comparison, the intermittent line indicates analogous data obtained by Barlow and Verrillo (1976). (Reprinted from Bolanowski, 1987, with permission from Elsevier)

in rough agreement with the comparable results of Barlow and Verrillo (1976) shown in the first chapter. The monocular curve of Fig. 3.16 together with the standard-error bars of the individual brightness estimates is reproduced in Fig. 3.17 for comparison with the results of the binocular experiment shown in terms of the geometric means and an interpolating curve. The intermittent line indicates the results of Barlow and Verrillo. The ordinates of the binocular data are about twice the ordinates of the monocular ones in approximate agreement with perfect arithmetic summation. Thus, the law of additivity is conserved in vision for ganzfeld illumination.

Chemical senses – olfaction and gustation, do not appear to be subject to arithmetic additivity in the sense that hearing, touch and vision in ganzfeld illumination are. According to authoritative studies, the additivity that can be found is incomplete in most instances, but, in some instances, there may be what has been called "hyperadditivity" – the sum exceeds arithmetic addition.

With respect to olfaction, Cain (1977) found by magnitude estimation for n-butyl alcohol that an odorant delivered to both nostrils appears stronger than when delivered to one only. The ratio does not depend on odor intensity, in agreement with arithmetic additivity. However, it is smaller than two. The reduced ratio could mean partial addition, but Cain showed that it is due most probably to adaptation. A preceding stimulus delivered to one nostril makes the following stimulus appear less intense in either nostril. Accordingly, addition is preceded by a mutual interaction in contradiction of the law of additivity. Burglund and Olsson (1993) found a similarly incomplete addition between odorants that are different from each other. Here too, the deficit in additivity was approximately independent of odorant intensity.

Incomplete additivity is also found in gustation, but in many instances hyperadditivity takes place. The latter often occurs in the sweetness of sugars, as found for example by Moskowitz (1973) who used the taste and spit method and normalized magnitude estimation. The effect may have been exaggerated by the method. Bartoshuk and Cleveland (1977) who applied a similar psychophysical method, found that it is smaller, if present at all, when a flow method is used in which the substance to be tested is made to flow over the tongue. With this method, the sweetness of sugars increased with their concentration according to power functions with exponents approximating unity, and the sweetness magnitudes of sugar mixtures appeared to be additive. However, the direct proportionality associated with the unity exponent prevented an unequivocal conclusion that true additivity took place. Otherwise, Bartoshuk and Cleveland did not find the results compatible with arithmetic additivity with either method. In general, gustatory substances are likely to interact with each other before summation of their subjective magnitudes, and the presence of one substance tends to change the taste and apparent intensity of another substance with a different taste. There are exceptions, however. They are encountered in bitter substances. For example, adaptation to QHCL does not reduce the bitterness of urea; neither adaptation to QHCL nor to urea reduces the bitterness of PTC; adaptation to caffeine does not reduce the bitterness of urea and vice versa (Bartoshuk and Cleveland, 1977). Perhaps in these cases, arithmetic additivity of subjective taste magnitudes is possible. Otherwise, it appears to be questionable in chemical senses.

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