Effects of aging on the suprathreshold responses to vibration

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The psychophysical responses to vibration of two age groups (22 or 25 and 66 years) were compared for two tasks using suprathreshold levels of vibrotactile stimulation. At a vibration frequency of 25 Hz, the two age groups gave similar curves of subjective magnitude determined by the method of absolute magnitude estimation. At 250 Hz, the curve of the older group showed no recruitment over low levels of intensity. Instead, their magnitude estimates were depressed over the entire range of intensities. Sensory persistence, measured by a matching procedure, was more marked in the older group.

The effect of aging upon the absolute detection threshold for vibration has been reported in a number of publications (Cosh, 1953; Frisina & Gescheider, 1977; Goldberg & Lindblom, 1979; Howell, 1947; Laidlaw & Hamilton, 1937; Mirsky, Futterman, & Broh-Kahn, 1953; Pearson, 1928; Rosenberg, 1958; Steiness, 1957; Verrillo, 1977, 1979, 1980; Whanger & Wang, 1974). In general, these studies report a loss of sensitivity as age increases. Verrillo (1979, 1980) showed that the loss was frequency selective; between the ages of 10 and 65 years, there was no change in threshold at low frequencies, but there was a substantial loss at higher frequencies. At 250 Hz, sensitivity decreased by approximately 19 dB between 10 and 65 years of age. The differential loss was interpreted within the duplex theory of mechanoreception (Verrillo, 1968) to indicate that anatomical changes with age within the Pacinian receptor system could account for the loss at 250 Hz, whereas functional characteristics of the non-Pacinian receptor systems could account for the stable threshold at 25 Hz. The loss of sensitivity reported for the higher frequencies is consistent with sensory losses noted in other sense modalities (Corso, 1977; Engen, 1977; Fozzard, Wolf, Bell, McFarland, & Podolsky, 1977; Kenshalo, 1977).

The effect of aging on responses to suprathreshold stimulation has not been investigated for the vibrotactile systems. The experiments reported here were designed to investigate two aspects of these responses. In the first experiments, the growth of subjective

magnitude as a function of stimulus intensity was compared in two age groups using a method of magnitude estimation (Stevens, 1957). In the second set of experiments, the phenomenon of sensory persistence was compared in the same age groups using a matching technique.

METHODS AND PROCEDURES

The apparatus used in these experiments consisted of the appropriate equipment to produce, time, and amplify sinusoidal signals, which were delivered to a vibrator mounted on an adjustable platform beneath a rigid surface (Verrillo, 1968). The contactor was 2.9 cm² and protruded through a hole in a rigid surface greater by 2 mm than the diameter of the contactor. The rigid surround prevented surface waves from spreading across the skin. The contactor was pressed into the skin .5 mm beyond minimum contact to prevent decoupling during the sinusoidal oscillations. Vibration amplitude was monitored by a precision accelerometer mounted beneath the contactor directly on the moving element of the vibrator. All measurements were made on the thenar eminence of the right hand.

The signals used in the magnitude-estimation experiments were 25- and 250-Hz bursts of 600 msec duration with a 1,400-msec interstimulus time interval. The rise-fall time was 100 msec measured at the half-power point. Following threshold determination by a modified method of limits, the subject was presented with a random series of 10 different intensities ranging from 2 to 50 dB SL. Three series were presented at each frequency. The subject was instructed to assign to each intensity a number that represented his or her subjective impression of how intense the stimulus was. No standard or modulus was given, in accord with the method of absolute-magnitude estimation (Zwislocki, 1978; Zwislocki & Goodman, 1980). The signal was repeated until a number was assigned by the subject, at which time it was turned off and the number was recorded. The next intensity was then presented following an alert light to the subject. Typically, a number was assigned after three repetitions of the stimulus. The geometric mean of the second and third runs was taken as the estimate at each intensity level.

The method used to measure sensory persistence was originally developed to measure loudness enhancement (Irwin & Zwislocki, 1971; Zwislocki & Ketkar, 1972; Zwislocki, Ketkar, Cannon, & Nodar, 1974; Zwislocki & Sokolich, 1974) and was used successfully to measure the phenomenon of enhancement of vibrotactile sensations (Gescheider, Verrillo, Capraro, & Hamer, 1977; Verrillo

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Figure 1. Stimulus paradigm used to measure sensory persistence. See text for explanation.

& Gescheider, 1975, 1976, 1979b). The stimulus paradigm consists of three short (20-msec) sinusoidal bursts with rise-fall times of 25 msec as measured at the half-power points: the conditioning stimulus, the test stimulus, and the matching stimulus (Figure 1). Following the threshold measurement of the test stimulus alone, it is raised 10 dB and the subject is then required to make a control match by adjusting the intensity of the matching stimulus to that of the test stimulus. Control matches were made at the start and finish of each testing session, and the results of the two matches were averaged. Adjustment is made by means of an unmarked knob attached to a smooth 120-dB logarithmic attenuator. The time interval between the test and matching stimuli was a constant 750 msec. The control match was typically accurate within ± 1.0 dB. The intensity of the conditioning stimulus was set an additional 10 dB above the 10-dB SL of the test stimulus.

Following the control match, the subject was asked to match the intensity of the matching stimulus to that of the test stimulus, but now in the presence of the conditioning stimulus. For the experimental matches, the time interval between the conditioning and test stimuli (Δt) was varied randomly from 75 to 500 msec. The difference in decibels between the control and experimental matches is a measure of the influence of the conditioning stimulus

upon the test stimulus plotted as a function of Δt . This phenomenon (enhancement) may be viewed as a measure of persistence, within the nervous system, of the conditioning stimulus over the time interval between the conditioning and test stimuli.

Two groups of six subjects each were tested. The subjects were paid volunteers. The elderly group was not institutionalized. One group had a mean age of 25 years (median age 25 years) and a range of 19 to 30 years. The other group ranged in age from 59 to 84 years with a mean of 66 years (median age 67 years). There were three men and three women in each group. Responses to questioning indicated that all of the subjects were in good health, and none reported symptoms of neurological impairment.

RESULTS AND DISCUSSION

Subjective Magnitude

Before presenting the results of the present experiments, I should like to point out that data are shown in Figure 2 which indicate that, at 25 Hz, the thresholds of subjects averaging 65 years of age are not dif-

Figure 2. Comparison of absolute thresholds of detection as a function of stimulus frequency for two age groups, 65 years (closed circles) and 20 years (open circles) of age. At 25 Hz, the difference between the groups is insignificant, but at 250 Hz, the older group is approximately 19 dB less sensitive than the younger group. (Data taken from Verrillo, 1979, 1980)

ferent from those of a group averaging 20 years of age (Verrillo, 1980). However, the 65-year-old group was approximately 19 dB less sensitive at a frequency of 250 Hz. Stevens (1968) argued that the decrease of vibrotactile sensitivity at low frequencies was analogous to a loss of sensitivity due to peripheral damage at the cochlea. He reasoned that the growth of subjective sensitivity, therefore, should be more rapid at low frequencies, a phenomenon known as loudness recruitment in persons with damage within the organ of Corti (Fowler, 1928; Hellman, 1981; Hellman & Zwislocki, 1964; Miskolczy-Fodor, 1964; Pohlman & Kranz, 1924; Steinberg & Gardner, 1937; Stevens & Guirao, 1967; Thalmann, 1965). Loudness recruitment appears as a rapid growth of subjective intensity near threshold, but at higher stimulus intensities the curve approximates the normal loudness function. Retrocochlear damage (neural) results in a downward shift of the entire loudness function, but without recruitment (Davis, 1947; Hirsh, 1952; Thalmann, 1965). Vibrotactile curves of subjective magnitude are indeed slightly steeper at 25 Hz than at 250 Hz (Stevens, 1968; Verrillo, Fraiolo, & Smith,

Figure 3. Absolute magnitude estimation (geometric means) of a 25-Hz signal for two age groups, plotted as a function of stimulus intensity in dB re 1.0 μm of peak displacement. Both sets of data (25 years, open circles; 66 years, closed circles) could be fitted by the same curve whose slope at the lower intensities is 1.2 ($r = .96$) and at the upper intensities, .46 ($r = .97$).

Figure 4. Same as Figure 3, but at a frequency of 250 Hz. The curve for the older group (closed circles) does not show a recruitment effect at intensities near threshold, where the slope is 1.2 for both groups (66 years, $r = 1.0$; 25 years, $r = .98$). There is a deficit in perceived magnitude at all stimulus intensities in the older group. The slope for the older group at higher intensities is .43 ($r = .99$) and for the younger group, .38 ($r = .99$). Standard error bars are shown.

1969), but the slopes are approximately the same at frequencies above 25 Hz.

Predicting by analogy to the auditory model, we should expect that the similarity of thresholds at 25 Hz in the two age groups (Figure 2) would result in similar curves of subjective magnitude. The results in Figure 3 do show that, at 25 Hz, the growth of sensation for the 66-year-olds closely approximates that of the younger group. Curves for the two groups, fitted by the method of least squares, were so close that it was possible to draw a single curve to represent both sets of data (upper slope = .46, $r = .97$; lower slope = 1.2, $r = .96$). Again, by analogy, we should expect that the rather substantial loss in sensitivity at 250 Hz (Figure 2) for the older group should result in a recruitment effect (receptor changes), in a downward shift of the entire curve of subjective magnitude (neural change), or in both. The results in Figure 4 show that only the downward shift is present. The curve of the 66-year-old group is no steeper near threshold than is that of the 25-year-olds (slope = 1.2, $r = 1.0$, both groups). At higher intensities, the

curve of the older group is shifted downward and is steeper (slope = .43, $r = .99$) than the curve of the younger group (slope = .38, $r = .99$). Use of the t test showed the difference between the slopes of the two groups to be statistically significant ($p < .01$, $df = 8$). The variability in the two age groups was similar. For the 25-Hz data (Figure 3), the standard errors of the mean (Alf & Grossberg, 1979) for the younger group ranged from .01 to 7.0; for the older group, they ranged from .01 to 6.9. For the 250-Hz data (Figure 4), the standard errors for the younger group ranged from .02 to 3.37; for the older group, they ranged from .02 to 2.34.

Reasonable hypotheses can be developed to explain the findings shown in Figure 4. It has been shown that, at 250 Hz, the psychophysical response to vibration is determined by activation of the Pacinian-capsule receptor system (Talbot, Darian-Smith, Kornhuber, & Mountcastle, 1968; Verrillo, 1963, 1966a, 1966b, 1968; Verrillo & Gescheider, 1979a). The decrease of vibrotactile sensitivity at 250 Hz that occurs with age may be attributed to several age-related changes within the population of Pacinian corpuscles (Verrillo, 1977, 1979, 1980). As age increases, lamellae are added by apposition to the capsular structure of the corpuscle (Cauna, 1965), resulting in a substantial enlargement of the receptor and possibly a change in the filter characteristic of the capsule (Loewenstein & Skalak, 1966; Verrillo, 1979, 1980). This change could be associated with the loss of sensitivity at high frequencies (Figure 2), but the loss apparently has no effect on the rate of growth of subjective magnitude at intensities near threshold (Figure 4, 250 Hz) for the 66-year-old group. In addition to changes in structure, the population of Pacinian corpuscles reduces with age (Cauna, 1965). Since spatial summation is a characteristic of this system and not of the non-Pacinian system (Verrillo, 1963, 1966c), the reduction in number also may account for the lowered sensitivity at 250 Hz as well as the shift in the entire subjective-magnitude curve (Figure 4) of the 66-year-old group. The similarity of slope at the lower intensities is consistent with Zwislocki's (1974) hypothesis that, near threshold, the growth of the subjective magnitude is proportional to the responses of individual nerve fibers and that, at higher intensities, it is more closely related to the activity of the entire nerve bundle (Hellman & Hellman, 1975).

The steeper slope at higher intensities for the older group is also consistent with the finding that, when measurements are made at different sites on the body having different densities of corpuscles, the slopes of the curves vary inversely with the receptor density (Verrillo & Chamberlain, 1972). Furthermore, when estimates are made using different contactor sizes, the smaller contactor, stimulating fewer receptors, results in a steeper curve of subjective magnitude

(Verrillo, 1974). These results and those of the present study suggest that the position and slope of the curve for the older group relative to the younger group are linked to the reduction in the number of Pacinian corpuscles that occurs with age.

Returning briefly to the changes with age that occur in hearing, in an older population both recruitment near threshold and a reduction of loudness at higher stimulus intensities may be measured and have been associated with a mixture of degenerative changes in the organ of Corti and with losses within the retrocochlear neural chain (Goetzinger, Proud, Dirks, & Embry, 1961; Hansen & Reske-Nielsen, 1965; Schuknecht, 1967; Schuknecht & Igarashi, 1964). We cannot, at the present time, identify with certainty the neural mechanisms responsible for the psychophysical changes in vibrotactile threshold and in subjective magnitude (Figures 2 and 4) that occur with age, but they appear to be analogous only to the retrocochlear changes that occur in the auditory system. There seems to be no parallel to the changes that occur within the organ of Corti and the consequent recruitment phenomenon.

Sensory Persistence

Sensory persistence occurs when a sensation is prolonged psychologically for some time after the offset of the physical stimulus. (For a review and analysis of visible persistence, see Botwinick, 1978, and Coltheart, 1980). Coltheart proposes that persistence of visible stimuli depends on prolonged activity both at the level of the receptor and at stages along the visual pathways. The phenomenon has been investigated using a wide variety of methods. It has been reported, not only in vision, although the preponderance of the literature concerns that modality, but also in hearing and touch (Coltheart, 1980). Visual persistence lasts longer in older subjects (Amberson, Atkeson, Pollack, & Malatesta, 1979; Brozek & Keys, 1945; Kline & Birren, 1975; Kline & Szafran, 1975; McFarland, Warren, & Karis, 1958; Misiack, 1951). Mundy-Castle (1953) found that the EEG response to photic stimuli is prolonged as age increases.

A phenomenon closely related to persistence is enhancement, in which a brief stimulus has a measurable effect upon another stimulus that closely follows it in time. Sensory persistence and enhancement may be related by the same or similar underlying neural mechanisms, so it seems reasonable that the same method is used for measuring either phenomenon.

In the present experiments, two groups of subjects, whose mean ages were 22 and 66 years, were tested. There were three men and three women in each group. The subjects were tested by the method described above, using the stimulus paradigm shown in Figure 1. In one experiment, 300 Hz was used for the conditioning, test, and matching stimuli; in another,

25 Hz was used for all three stimuli. The subjects were tested three times at each frequency, and the results were averaged over the three runs.

The results shown in Figure 5 are for both 25 and 300 Hz and are compared with the curve of the group whose mean age was 22 years. The data for the 25- and 300-Hz conditions for the younger group were so similar that a single curve could be drawn through both sets of data points. The variability in the two age groups was very close. For the 300-Hz data (Figure 5), the standard errors of the mean for the younger group ranged from .11 to .34 dB and for the older group ranged from .14 to .39 dB. For the 25-Hz data, the standard errors for the younger group ranged from .06 to .32 and for the older group from .07 to .27.

The results at both frequencies indicated that the conditioning stimulus had a more profound effect upon the test stimulus at all time intervals for the 66-year-old group than it did for the 22-year-old group. This may be interpreted as a longer persistence of the effect of the conditioning stimulus upon the perceived intensity (enhancement) of the test stimulus. Note that the enhancement drops to an insignificant level in the younger group when Δt approaches 500 msec, whereas in the older group the

Figure 5. Effect in decibels of the conditioning stimulus on the subjective intensity of the test stimulus, plotted as a function of the interstimulus time interval (Δt). There was no frequency difference in the younger group, so their data are represented by a single, heavy, solid line. Measurements at two frequencies are shown for the older group (25 Hz, open circles; 300 Hz, closed circles). Standard error bars are shown.

elevation of perceived intensity is still above 1.0 dB. The reduction of the enhancement effect to approximately .5 dB in the older group did not occur until Δt was set at 600 msec (data point not shown). At short time intervals, it should be noted that no data points are shown at $\Delta t = 75$ and 100 msec. This is because five of the six older subjects could not perceive two stimuli (conditioning and test) at time intervals less than approximately 150 msec, whereas the younger group had no difficulty in making this discrimination. We have not systematically studied the minimum perceivable interval between two pulses in different age groups, but this result is consistent with the finding that temporal resolution of somesthetic stimuli declines with age, indicating an increase of persistence (Axelrod, Thompson, & Cohen, 1968).

It should be pointed out that when this experiment was performed using 25 Hz for the conditioning stimulus, with the test and matching stimuli set at 300 Hz, there was no enhancement (Verrillo & Gescheider, 1975, 1976). This would indicate that when Pacinian and non-Pacinian channels are separated at the periphery, interactions between the two systems do not occur, although there is a narrow band of frequencies at which the systems appear to overlap (Gescheider et al., 1977). In the 66-year-old group there was no effect when the combination 25-300-300 Hz was used for the three stimuli (data points not shown). Thus, for both age groups, enhancement (persistence) effects do not appear to cross between channels.

A major difference occurs in the data of the older group (Figure 5) that does not appear in the results obtained with younger subjects. At time intervals between 150 and 200 msec, the older group shows markedly greater enhancement at 25 Hz than at 300 Hz, a result that indicates a longer persistence effect within the non-Pacinian system. The younger group showed no such effect of frequency. This result complements the finding in vision that discrimination of low spatial frequencies is more affected by aging than that of high spatial frequencies (Sekuler, Hutman, & Owsley, 1980). It is generally accepted that the enhancement effect is most probably due to central rather than peripheral neural processing (Elmasian, Galambos, & Bernheim, 1980; Galambos, Bauer, Picton, Squires, & Squires, 1972). Loudness enhancement could not be detected electrophysiologically at the auditory nerve of cats (Bauer & Galambos, 1975), and the EEG recordings at the level of the brainstem in man revealed no effects for auditory stimuli (Bauer, Elmasian, & Galambos, 1975). Thus, the mechanism for enhancement probably is the result of information processing at higher levels of the CNS.

It is not possible at the present time to specify what changes occur with age within the nervous system that could account for these results. There is evidence

that cells receiving inputs from Pacinian and non-Pacinian mechanoreceptors are correlated with specific areas (Paul, Goodman, & Merzenich, 1972; Paul, Merzenich, & Goodman, 1972), as well as with the cytoarchitecture of somatosensory areas I and II (Bennett, Ferrington, & Rowe, 1980; Ferrington & Rowe, 1980; Hyvärinen & Poranen, 1978), but anatomical differentiation is not in itself sufficient to explain psychophysical results. Evidence of functional differentiation is shown by deficits in specific discrimination tasks provided by selective ablation of sites in the somatosensory cortex (Randolph & Semmes, 1974). Coupled with these findings is the evidence of extensive changes in central neurons that occur with age (Bondareff, 1977), although the functional significance of many of these changes is not certain.

Peripheral changes are known to occur within transmission neurons and nerve bundles, and at the receptor. The increase in size and the reduction in number of Pacinian corpuscles (Cauna, 1965) have been mentioned above. There are also, with age, changes in morphology and a reduction in the number of Meissner's corpuscles (Bolton, Winkelman, & Dyck, 1966; Cauna, 1965), one of the non-Pacinian receptors thought to be responsible for the low-frequency threshold response. These changes would not be expected to affect the threshold (Figure 2) or the growth of sensation (Figure 3) at 25 Hz, since the non-Pacinian system does not summate energy over space (Verrillo, 1963, 1966c). Although Cauna (1965) reports that both Pacinian and Meissner's corpuscles decline in number with age, he does not indicate if there is a differential loss between the two populations. It is not difficult to relate these anatomical changes with the psychophysical results at threshold (see Verrillo, 1969, 1980) and at suprathreshold levels (discussed above), but a change in the filter characteristics of the Pacinian corpuscle and a reduction in the number of Pacinian and Meissner's corpuscles do not appear to account easily for the frequency difference in older subjects shown in Figure 5.

The changes in neural structure and chemistry that occur with age are considerable in both the peripheral and central nervous systems, but there is insufficient correlative evidence to associate these changes with certainty to functional changes measured psychophysically. They do, however, suggest possible neural mechanisms for these changes.

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