Child and adult vibrotactile thresholds for sinusoidal and pulsatile stimuli

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Three experiments were performed to obtain vibrotactile sensitivity thresholds from hearing children and adults, and from deaf children. An adaptive two-interval forced-choice procedure was used to obtain estimates of the 70.7% point on the psychometric sensitivity curve. When hearing children of 5–6 and 9–10 years of age and adults were tested with sinusoids and haversine pulse stimuli, at 10, 100, 160, and 250 Hz or pps, respectively, only the 10-Hz stimulus resulted in an age effect. For this stimulus, young children were significantly less sensitive than adults. When sinusoids were again tested at 20, 40, 80, and 160 Hz, a small overall effect of age was observed with a significant effect only at 20 Hz. Two prelingually profoundly deaf children were tested with haversine pulse trains at 10, 50, 100, 160, and 250 pps. Both children were at least as sensitive to the tactile stimulation as were the hearing children and adults. Pulsatile stimulation, compared to sinusoidal stimulation, exhibited relatively flat threshold versus frequency functions. The present results, demonstrating no age effect for pulsatile stimulation and similar performance for deaf and hearing children, suggest that pulsatile stimulation would be appropriate in vibrotactile speech communication aids for the deaf.

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INTRODUCTION

Vibrotactile perception in normally hearing and deaf children has received only limited study. One reason for interest in age-related changes in vibrotactile perception is the possibility of using vibrotactile devices as speech communication aids for profoundly deaf children. It is likely that even a simple vibrotactile device can be of benefit to young deaf children (Goldstein and Proctor, 1985). As vibrotactile devices with increased capabilities are being developed, it is important to look for possible age-related changes in aspects of vibrotactile sensitivity. In the present report, thresholds were explored with hearing children at ages 5–6 and 9–10 years of age, and with two profoundly deaf children in the 9- to 10-year age range.

Previously, sensitivity thresholds for sinusoidal vibration were obtained from normally hearing children and adults by Verrillo (1977) and Frisina and Gescheider (1977). Verrillo tested six children between the ages of 8 and 12 years, and Frisina and Gescheider tested seven children between 8 and 11 years. Both studies reported somewhat greater sensitivity on the part of the children in comparison with the adults. Differences between the groups were observed primarily for the frequencies between 25 and 250 Hz. Below 25 Hz, thresholds were the same for both age groups. It was of interest to determine whether this age trend extends to children younger than 8 years of age.

When adults' sensitivity thresholds are tested, the shape of threshold curves is a function of stimulus waveshape. Verrillo (1968) has shown that sinusoidal stimulation to glabrous skin results in a U-shaped function with greatest sensitivity at approximately 250 Hz. Results with pulse trains are quite different. Rothenberg *et al.* (1977) report relatively flat thresholds between 20 and 250 pulses per second (pps) using 1.0-ms Gaussian shaped pulses presented to the volar forearm. Also, in strong contrast with results for sinusoidal stimulation, very little change in sensory magnitude has been observed for pulsatile stimulation (see also Sherrick, 1985). The relatively flat threshold and equal magnitude functions obtained with pulse trains suggest that pulsatile might be a better choice than sinusoidal waveforms for a tactile aid. We were interested in whether sensitivity threshold functions for pulse trains might be stable across age. The absence of an age effect would be additional support for the use of pulse trains in the implementation of tactile aids.

The previous studies of children by Verrillo (1977) and Frisina and Gescheider (1977) made use of the Békésy (1939) tracking method, which is susceptible to changes in criterion as a function of age. That is, children may differ from adults in the level of certainty they require before reporting that a stimulus is present. In our experiments, thresholds were obtained using a conventional two-interval forced-choice procedure. This procedure is much less susceptible to the effects of criterion placement, since the subject is never asked to report presence versus absence of a stimulus but must always report the interval in which the stimulus is most likely present. The two-interval forced-choice procedure does, however, appear to place a lower limit on the age at which children can be tested. Preliminary testing of 4-year-olds suggested that only toward the end of the fourth year was it possible for them to learn the procedure.

Two experiments are reported below for which normally hearing children were tested. In addition, data were collected from two profoundly deaf 10-year-olds.

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I. EXPERIMENT I. COMPARISON BETWEEN SINUSOIDS AND HAVERSINES

A. Subjects

Thirty-six subjects were tested, six in each group defined by age and type of stimulus tested. Subjects tested with sinusoidal stimuli were mean age 5 years 6 months (range 4 years 10 months to 5 years 11 months), mean age 9 years 10 months (range 9 years to 10 years 6 months), and adults mean age 21 years (range 18 to 21 years). Subjects tested with haversine stimuli were mean age 5 years 7 months (range 4 years 10 months to 6 years 8 months), mean age 9 years 9 months (range 9 years 5 months to 10 years 4 months), and adults mean age 21 years (range 18 to 21 years). Each group was balanced for sex, except for the group of 9- to 10-year-olds tested with sinusoids. In that group, there were four girls and two boys. All subjects were paid for their participation.

B. Apparatus

The vibrator assembly was modeled after one used by Verrillo (1962). An AV-6 vibrator (Alpha-M Corporation, Euless, TX) was mounted under a table so that the contactor protruded through a plate drilled such that the hole was 1 mm greater in radius than the contactor. The surface of the aluminum contactor touching the skin was a 0.28-cm^2 disk. The contactor height was adjusted for each subject before each test session. An electrical resistance measure was used to determine the point at which the probe tip made contact with the subject's right index finger. Then the probe was raised an additional 1 mm.

The vibrator was mounted on a "sandwich" of wood, metal, and sound-absorbing foam in order to damp various resonances. A jack under the sandwich was used to adjust the contactor height. In order to prevent vibration from being transmitted through the floor to the subject, the entire assembly was placed on a cast iron pedestal.

Two transducer systems were used to monitor the stimulus. An accelerometer was mounted on the vibrator probe and was used for calibration at frequencies above 100 Hz. An optical sensor was also mounted on the vibrator assembly, and was used to monitor waveshape and to calibrate displacement at frequencies below 100 Hz. A notch filter was built to compensate for the vibrator's principal resonance. A compensation network was used to extend the range of usable frequencies. As a result, the vibrator frequency response was flat to 500 Hz.

Stimulus synthesis, presentation, and response collection were accomplished using a DEC LSI 11/73 computer. Stimuli were converted from digital samples by a 12-bit Adac digital-to-analog converter.

The same apparatus was used in experiments 2 and 3.

C. Stimuli

Stimuli were digitally synthesized sinusoids and 400-Hz haversine pulses. The sampling rate was 10 000 Hz. The haversine pulse is 1 cycle of a raised 400-Hz sinusoid $[A(\cos \omega t + 1), -\pi < \omega t < \pi]$. Thus pulses were 2.5 ms in total duration. Stimulus duration was 1 s. Sinusoid frequencies were synthesized at 10, 100, 160, and 250 Hz. Haversine pulse rates were generated at corresponding repetition rates. Sinusoidal stimuli were synthesized with 50-ms rise–fall times. Stimulus amplitude was changed in 2-dB steps. The method of stimulus generation was the same in experiments 2 and 3.

D. Procedures

Thresholds were obtained using the adaptive method of transformed up–down testing (Levitt, 1971) and a two-interval forced-choice procedure. The adaptive rule was such that two correct responses resulted in a 2-dB step down in stimulus amplitude, and one incorrect response resulted in a 2-dB step up in amplitude. Twelve reversals in direction of testing were used to estimate the 70.7% point on the psychometric threshold function. The threshold was taken as the mean of the final six midrun averages. A run was bounded by the stimuli at two consecutive changes in direction. The initial observation level was determined by setting a passive attenuator so that the subject reported that the stimulus felt weak but detectable.

A series of training tasks was devised in order to teach the button-press response to the children. The sequence of events for each trial was the same as that used during threshold testing. Each trial began with 750-ms warning lights. A 750-ms pause followed. A 1-s light was turned on during the first observation interval, followed by a 750-ms pause, followed by a 1-s light marking the second observation interval. The response interval was terminated by the subject's button-press response, and a 750-ms light was turned on above the correct button. A 3-s intertrial interval followed.

In each of three training tasks, a suprathreshold stimulus was presented during one of the two observation intervals. The stimulus was always a 100-Hz or 100-pps signal, depending on the stimulus condition to which the subject was assigned. First, the stimulus was presented only during the first observation interval, and the subject was required to learn the association between the stimulus presentation in that interval and the appropriate button-press response. A light was turned on to provide feedback signaling the correct interval after each response. Ten consecutive correct responses were required before training was given on the second interval. The same criterion for response was required for the second interval. Then training proceeded to the second task, in which the stimulus presentation interval was randomized, and subjects were required to respond correctly to a suprathreshold stimulus on 15 out of 20 trials. This level of response corresponds to a significance level of $p < 0.02$, according to the binomial distribution. Finally, a practice threshold was then obtained either at 100 Hz or 100 pps, depending on the condition to which the subject was assigned. Suprathreshold training was readministered at the beginning of every subsequent test session. Adults were given training in the same manner as the children so that conditions did not vary across age.

Thresholds at each of the four frequencies were obtained three times from each subject. Order of presentation of frequencies was randomized. Testing at a given frequency was at intervals of at least one week. The first set of four thresholds was considered practice and was not analyzed. The second and third sets were analyzed as test and retest data.

During testing, after a randomly chosen number of trials, children were rewarded by being allowed to choose a colorful sticker. This procedure proved extremely motivating and was probably in part responsible for maintaining their interest over the five to eight test sessions required to obtain a complete set of data.

Subjects wore Noisefoe Mark IV earmuffs during testing. Masking noise was not used because it was felt that noise would disrupt the performance of the very young children. The vibrator was extremely quiet, and pretesting was conducted to make sure that acoustic signals were not detectable in the range of displacements and frequencies presented.

The same procedures were used in experiments 2 and 3.

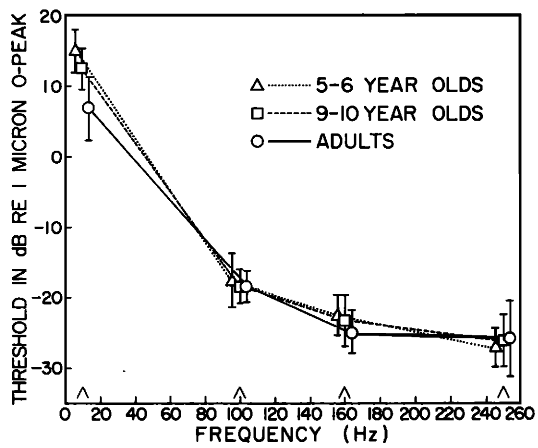

FIG. 1. Mean thresholds for 5- to 6- and 9- to 10-year-olds and adults tested with sinusoidal stimuli. Vertical bars indicate standard deviations. Arrows along the abscissa indicate the frequencies at which stimuli were presented.

E. Results

All of the children and adults successfully passed the criterion for threshold training and completed the entire procedure. In order to investigate whether the testing procedure was reliable, a repeated measures analysis of variance was performed on the number of trials required to obtain each threshold. Since thresholds were obtained adaptively, factors such as fatigue or lack of attention to the task could result in increased errors and, in turn, a larger number of trials. Between factors in the analysis were three ages × two sexes × two conditions (sinusoid or haversine). The one within factor was frequency (10, 100, 160, and 250 pps or Hz, depending on the condition). There was a small but significant effect of sex $F(1,24) = 5.29$, $p < 0.031$. Overall, the mean number of trials was 44.5 for females and 46.3 for males. However, a significant four-way interaction was also obtained among frequency, condition, sex, and age, $F(6,72) = 3.81$, $p < 0.003$. Further analysis showed that a significant interaction between age and sex for thresholds at 100 pps haversine stimuli was responsible for the four-way interaction, $F(2,12) = 3.98$, $p < 0.048$. Females at age 10 years required approximately ten fewer trials than males when tested with 100-pps haversine stimuli. Since we cannot readily attribute particular meaning to this result, we would suggest that the method was generally successful across all subjects. The absence of an effect of repeated testing suggests that the training procedure and collection of practice thresholds at all frequencies were effective in establishing the test paradigm among all subjects.

The thresholds obtained in experiment I are presented in Figs. 1 and 2. Each point is the mean across the test and retest thresholds obtained at each rate by each age group. Standard deviations are given by the vertical bars. Comparison of the curves in Figs. 1 and 2 clearly shows an effect of waveshape.

A repeated measures analysis of variance was performed on the obtained thresholds. Between factors were three ages × two sexes × two conditions (sinusoid or haversine). The one within factor was frequency (10, 100, 160, and 250 Hz or pps, depending on the condition). The effect of sex was significant, $F(1,24) = 4.29$, $p < 0.05$, and there were no interactions involving this factor. Males were consistently more sensitive than females by approximately 2.4 dB.

The effect of repeated testing was significant, $F(1,24) = 11.91, p < 0.003$, and there were no significant interactions involving this variable. For all subjects, the effect of retesting was to obtain slightly lower thresholds. Across all subjects, thresholds dropped by approximately 1.2 dB. For that reason, in Figs. 1 and 2 test and retest data were averaged within the age groups for each condition.

A significant main effect of frequency was also obtained, $F\ (3,72) = 858.31$, $p \cong 0.0$, as were interactions between frequency and age, $F\ (6,72) = 4.10, p < 0.002$, and frequency and condition, $F\ (3,72) = 234.44$, $p \cong 0.0$. An examination of Figs. 1 and 2 reveals that the shapes of the threshold functions for sinusoid and haversine stimuli are quite different, explaining the frequency × condition interaction. In both figures, threshold drops as a function of increased frequency or pulse rate, respectively. The shape of the threshold function for sinusoids (Fig. 1) is typical of results reported elsewhere, for example, by Verrillo (1968) and Sherrick and Craig (1982). The threshold drops steeply, by approximately 32 dB, for adult subjects. The threshold functions for

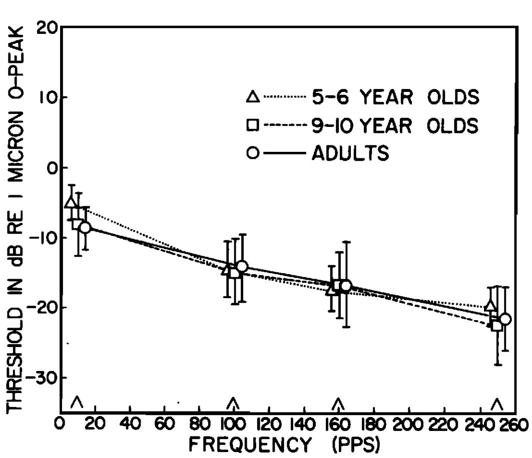

FIG. 2. Mean thresholds for 5- to 6- and 9- to 10-year-olds and adults tested with haversine stimuli. Vertical bars indicate standard deviations. Arrows along the abscissa indicate the pulse rates at which stimuli were presented.

haversine stimuli are also typical of published results for pulsatile stimulation to adult subjects (Rothenberg *et al.*, 1977); that is, the functions are relatively flat and lack the sharp decrease in threshold exhibited for sinusoidal stimulation.

Because a significant frequency by age interaction was obtained, simple analyses of variance were performed at each frequency for each condition. The only significant effect obtained from the simple analyses was for age at the sinusoidal frequency of 10 Hz, $F(2,12) = 6.87$, $p < 0.01$. Newman–Keuls Tests showed that the difference between five-year-olds and adults was significant, $p < 0.05$, but no other comparisons reached significance.

Some of the children commented on the difference in quality between the 10-Hz stimuli and the higher frequencies. At 10 Hz, the stimuli felt like a "wobble," in contrast with the higher frequency stimuli that provided a feeling of vibration. Some of the younger children expressed a dislike for the 10-Hz stimuli, suggesting that the qualitative difference added some additional difficulty to their task.

Previous work by Verrillo (1977) and Frisina and Gescheider (1977) using the Békésy tracking method had shown decreased sensitivity to sinusoidal stimulation as a function of age. Inspection of their figures revealed that the age effect they report is in the frequency region between 25 and 250 Hz, with the largest differences in the region between approximately 25 and 100 Hz. Since the frequencies tested in experiment I were not within this range, experiment II was conducted in which sinusoidal frequencies of 20, 40, 80, and 160 Hz were tested.

II. EXPERIMENT II. SINUSOIDS

A. Subjects

Five subjects were tested in each age group. The youngest subjects were mean age 5 years 5 months (range 4 years 11 months to 6 years 3 months). The older children were mean age 10 years (range 9 years 3 months to 10 years 10 months). The adults were mean age 19 years (range 18 to 19 years). Among the younger children, all except one were female. Two older children were female and three were male. All but one of the adults were male. All subjects were paid for their participation.

B. Stimuli

Stimuli were sinusoids synthesized at 20, 40, 80, and 160 Hz. Stimuli had 50-ms rise–fall times. Stimulus amplitude was scaled in 2-dB steps.

C. Results

All of the children and adults successfully passed the criteria for threshold training and completed the entire procedure. As in experiment I, a repeated measures analysis of variance was performed on the number of trials required to obtain each threshold. The factors were three ages × four frequencies (20, 40, 80, 160 Hz). No significant effects were obtained, suggesting again that a satisfactory, reliable procedure had been employed.

A repeated measures analysis of variance was performed on the obtained threshold values with the factors age and frequency. The repeated measures factor was not significant, and both sets of thresholds were averaged for Fig. 3. Figure 3 also shows the data from experiment I. It can be seen that the results from experiment II were generally well predicted on the basis of curves drawn for experiment I.

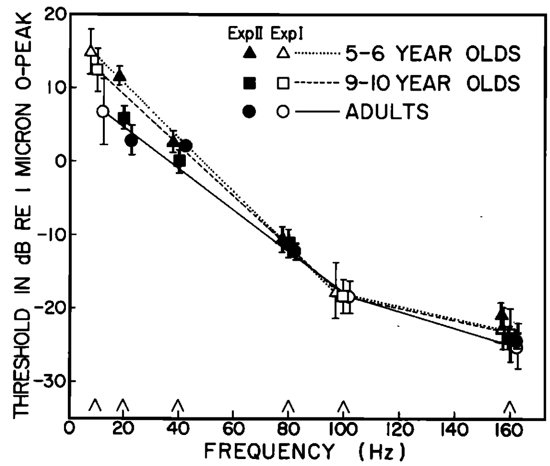

FIG. 3. Mean thresholds for 5- to 6- and 9- to 10-year-olds and adults in experiments I and II tested with sinusoidal stimuli. Vertical bars indicate standard deviations. Arrows along the abscissa indicate the frequencies at which stimuli were presented. (Note that the scale along the abscissa is expanded relative to Fig. 1.)

The analysis of variance showed, as expected, that frequency was a significant factor, $F(3,36) = 440.33$, $p \cong 0.0$. As can be observed in Fig. 3, threshold dropped as a function of frequency. Figure 3 also shows that, at all frequencies, the youngest children were slightly less sensitive than the other subjects. The older children's thresholds were between those of the younger children and the adults except at 40 Hz, where they were more sensitive than adults. The effect of age did not quite reach overall statistical significance, $F(2,12) = 3.16$, $p < 0.079$.

The subject groups for experiment II were not balanced for sex, because the preliminary analysis of experiment I data failed to reveal any effects due to sex. This lack of balance may be to some extent a contributor to the slight overall effect of age in experiment II, since males were found to be slightly more sensitive than females in experiment I, and the youngest subjects were mostly female while the adults were mostly male in experiment II.

Figure 3 shows that the largest difference between children and adults was at 20 Hz. The difference between the adults and younger children was significant for the 20-Hz stimuli, $t(8) = 3.74$, $p < 0.01$. Thus, in both experiments I and II, at the low frequencies of 10 and 20 Hz, young children were significantly less sensitive than adults.

III. EXPERIMENT III. THRESHOLDS OF DEAF CHILDREN

Since one of the purposes of our work was to provide information that might be useful in designing a vibrotactile aid that could be used by a prelingually profoundly deaf child, we were interested in whether deafness might have a significant effect on tactile sensitivity thresholds. As a result of experiment I, which showed no age effects with pulsatile stimulation, it was decided to use haversine pulses to test sensitivity in two prelingually profoundly deaf children.

A. Subjects

One female and one male were tested. The female was 10 years 7 months, and the male was 9 years 8 months. The female, T. K., previously used a single channel vibrotactile device when she was 30–39 months old (Goldstein *et al.*, 1983). During that period, she wore a vibrotactile aid mounted against her sternum an average of 2 h a day. At this time, she is in a mainstream program at school. She communicates with her parents and brother principally through signing. T. K. was profoundly deaf within the first postnatal month. She has no other handicapping conditions. T. K. does have conventional hearing aids at this time but does not use a vibrotactile aid. Audiograms indicate no response in either ear at 110 dB HL above 250 Hz. Below 250 Hz, no response was obtained at an average of 85 dB HL. The male, S. B., was diagnosed as being profoundly congenitally deaf. S. B. has no other handicapping conditions. He uses neither a conventional hearing aid nor a tactile aid. He communicates principally through lipreading and oral speech. His audiogram indicates a flat loss at 105 dB HL above 500 Hz and averages 80 dB HL at 500 Hz and below in the better ear.

B. Stimuli

Stimuli were haversine pulse trains synthesized at pulse rates of 10, 50, 100, 160, and 250 pps. Stimulus duration was 1 s, and amplitude was scaled in 2-dB steps.

C. Results

Testing of these children was straightforward. They readily understood the task, and the number of trials required to obtain thresholds from them was mean 42, somewhat less than for the normally hearing children overall.

Test and retest results are shown for both children in Fig. 4. The figure also gives the means and standard deviations for all subjects in experiment I. It can be seen in Fig. 4 that both children were generally at least as sensitive, if not more so, than the group of normally hearing subjects. T. K. was somewhat more sensitive than S. B.

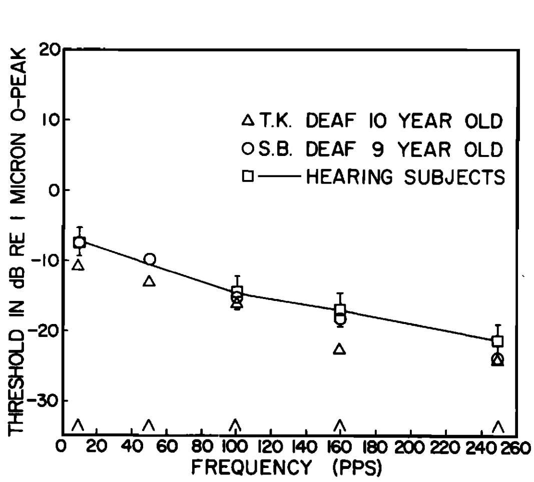

FIG. 4. Mean thresholds for profoundly deaf children and all subjects in experiment I tested with haversine stimuli. Vertical bars indicate standard deviations for subjects in experiment I.

IV. DISCUSSION AND CONCLUSIONS

Our results have shown that the threshold curves for adults and children are the same when stimulation is haversine pulses. Further, the shape of the curve is quite flat, in comparison with curves resulting from sinusoidal stimulation. These results are in general agreement with reports by Rothenberg *et al.* (1977), in which sinusoidal and pulsatile stimuli were compared.

Verrillo (1968) has presented evidence that two systems determine responses to vibratory stimuli: the Pacinian system and the non-Pacinian system. Spectral analysis of the haversine pulse trains indicates that the haversine pulse stimuli have frequency components in the vicinity of 250 Hz, the region in which the Pacinian corpuscle has been shown to be most sensitive (Verrillo, 1968). For example, the frequency components in the vicinity of 250 Hz for the 10-pps haversine pulses are approximately 4 dB down from the 10-Hz component. It appears likely that the relatively flat threshold response curves obtained with these stimuli can be accounted for in terms of the presence, at all pulse rates, of components for which the Pacinians are most sensitive.

Our results for sinusoidal stimulation are in general agreement with those reported by Verrillo (1977) and Frisina and Gescheider (1977) in that we observed only relatively small differences in sensitivity between older children and adults. However, our data indicate significantly less sensitivity at low frequencies for the younger children, whereas the previous studies showed equal thresholds for children and adults at low frequencies and somewhat greater sensitivity on the part of children at higher frequencies. A possible explanation for the discrepancies is the difference in testing procedures (Békésy tracking was used in the previous studies). Since the current study used a two-interval forced-choice procedure, it was less susceptible to systematic age effects related to criterion shifts that might have occurred previously. However, this explanation does not account for the frequency-dependent nature of our results.

Previously, Verrillo (1977) attributed age-span developmental changes in vibrotactile thresholds (across ages 10 to 65 years) to changes in the Pacinian corpuscle. Non-Pacinian receptors, most sensitive at low frequencies, were thought not to undergo ontogenetic changes. Our results indicate the strongest age effects at 10 and 20 Hz, frequencies for which the non-Pacinian receptors are most sensitive. However, we cannot simply conclude that physiologic change is responsible for our results. There is virtually no literature on development of the human somesthetic sense before age 10. The strong effect at extremely low frequencies suggests that physiologic change may be a principal factor for the low-frequency receptors. However, the children's comments suggesting that they perceived a qualitative difference in low-frequency stimuli points to the possibility of perceptual effects as well.

In the area of audition, it has been found that young children have poorer pure-tone sensitivity than older children or adults. Yoneshige and Elliott (1981) tested auditory pure-tone thresholds of 6-year-olds and adults and found children significantly less sensitive than adults. Additional studies of young children are needed to determine the patterns of sensitivity change within and across sensory systems. Information about synchronies or asynchronies in development across sensory perceptual systems can help to resolve questions about the relative contributions of physiologic and perceptual or cognitive factors to developmental effects.

Results of the current study suggest the following. (1) Pulsatile stimulation does not result in age effects, nor large thresholds shifts as a function of pulse rate and is therefore preferable for implementation of a vibrotactile communication aid. (2) Young children are less sensitive than older children or adults at low sinusoidal frequencies (i.e., in the vicinity of 10 and 20 Hz). (3) Deaf subjects, without additional handicapping conditions, do not differ from hearing adults or children tested with haversine stimuli.

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