Discrimination of vibrotactile frequencies in a delayed pair comparison task

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This study quantified human short-term-memory decay functions for delayed vibrotactile frequency discriminations. Subjects indicated which of two successive intervals contained the higher or lower frequency of a pair separated by delay periods of 0.5–30 sec. Performance decreased as a function of length of delay and was higher when delays were unfilled than when they were filled with a backwards-counting task. This interpolated task may have interfered with rehearsal of a coded representation of the remembered vibrotactile frequency. A change in decay rate after 5-sec delays suggests a switch from reliance on sensory memory to the coded frequency representation. Performance and decay rate depended on presentation order of higher or lower frequency within pairs. Reciprocal performance asymmetries seen in high- versus low-frequency ranges did not result from simple response bias.

In normal tactile exploration of objects, the hand gathers information by a sequence of movements over surfaces and contours (e.g., Lederman & Klatzky, 1987; Lederman, Klatzky, & Barber, 1985). As in visual exploration, some information is obtained in parallel from the semi-independent placement and movement of multiple foveal fingertips. However, at least for objects exceeding the grasp of the hand, complete examination necessarily proceeds sequentially, requiring retention of details by a mechanism or mechanisms referred to as *short-term* or *working* memory (e.g., Tulving, 1987). Melzack and Eisenberg (1968), for instance, reported skin sensory afterglows, in which touching the lip or inner nose with a filament could produce a “tingling” sensation that lingered for several minutes. Results of studies of memory using tactile stimuli, such as Braille letters, three-dimensional shapes, and position and order of punctate stimuli, support the proposition that tactile short-term memory is partially based on a continuing “trace” of the original sensation, sometimes called *sensory memory*, that gradually decays over a period of about 5–10 sec after stimulation ends (Davidson, 1972; Davidson, Barnes, & Mullen, 1974; Davidson & Whitson, 1974; Gilson & Baddeley, 1969; Heller, 1987; Hill & Bliss, 1968; Millar, 1974, 1975, 1977, 1978a; Sullivan & Turvey, 1972, 1974; Zung & Butter, 1974). Performance on some tactile discrimination tasks, in which a delay separates two stimuli, decrements over this same time period (Gilson & Baddeley, 1969; Sullivan & Turvey, 1972, 1974). However, presentation of a series of stimuli to the same skin site can be remembered even though each successive item replaces the previous

lingering sensation (Millar, 1978b). This suggests that short-term tactile memory depends on more than a persisting sensory trace. After about 5–10 sec, another mechanism, possibly involving some condensation or recoding of sensory information, may supersede use of the weakening sensory “image” (Millar, 1978a). The nature of this alternate mechanism is suggested by the finding that rehearsal, the intentional repetition of some form of the sensation in short-term memory (Posner, 1967), can improve performance on delayed discrimination tasks. Discrimination performance declines at a greater rate during delay periods filled with attention-demanding tasks (e.g., counting backwards in threes), which presumably interfere with mnemonic rehearsal (Dillon & Reid, 1969; Gilson & Baddeley, 1969; Peterson & Peterson, 1959; Sullivan & Turvey, 1972, 1974; Wells, 1972). For example, Gilson and Baddeley (1969) required subjects to identify the locus of stimulation of a probe applied to the forearm, after delays as long as 60 sec. They used up to 22 stimulation points at 1-cm spacings. On half the trials, they prevented “rehearsal” by requiring subjects to perform an interpolated task, counting backwards by three (Dillon & Reid, 1969; Peterson & Peterson, 1959; Wells, 1972), during a delay between stimulation and the opportunity to respond. Without rehearsal, accurate recall of the position of stimulation declined to a minimum near chance after 45 sec. With rehearsal, memory decayed at the same rate as without rehearsal until about 10 sec, at which point performance improved and then decayed to asymptote by 60 sec. This difference in the time course of declining performance between filled and unfilled delay conditions supports the notion that tactile short-term memory depends on two processes. The rapidly decaying sensory register, or sensory memory, provides the most accurate information during the initial 5–10 sec following stimulation. Beyond 10 sec, another mechanism—possibly involving some recoding of sensory information that, when augmented by rehearsal, decays at a slower rate—may supersede the information

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content of the weakening sensory image (Gilson & Baddeley, 1969; Millar, 1978a).

The purpose of the present study was to characterize memory-decay functions for stimuli suitable for use in neurophysiological studies of tactile memory. Stimulus control was therefore paramount. Vibration serves as a simple well-controlled stimulus for tactile studies. Many neurophysiological studies of visual memory use precisely specified stimuli that vary on simple dimensions, such as the color or orientation of bars (Desimone, Schein, Moran, & Ungerleider, 1985; Fuster, 1990; Fuster & Jervey, 1981; Maunsell, Sclar, Nealey, & DePriest, 1991; Moran & Desimone, 1985; Spitzer, Desimone, & Moran, 1988). The simplicity of these stimuli facilitates the correlation of remembered features with neural response patterns. Similarly, vibrotactile stimuli provide simplicity in feature identification for the tactile modality. Yet, although the discrimination functions for vibration have been described in detail (e.g., Mountcastle, LaMotte, & Carli, 1972; Talbot, Darian-Smith, Kornhuber, & Mountcastle, 1968; Verrillo, 1965), and this simple well-controlled stimulus has proved valuable in neurophysiological investigations of the somatosensory system (e.g., Burton & Sinclair, 1991; LaMotte & Mountcastle, 1979; Mountcastle, 1984), vibrotactile stimuli have not been used to examine tactile memory.

The main purpose of the present study was to investigate memory demand in delayed vibrotactile frequency discriminations in humans (Experiment 2). The effects on performance of filling the interval between discriminated stimulus pairs with an attention-demanding task were examined. A control experiment investigated the source of performance asymmetries associated with presentation order within stimulus pairs.

GENERAL METHOD

Subjects

The subjects were 4 male and 4 female students or employees at Washington University, ranging in age from 19 to 27 years. When asked to indicate the preferred hand, 7 subjects chose the right hand, and 1 chose the left. All subjects had normal or corrected-to-normal vision. Participation in the first two experiments required approximately 15 h per subject. A follow-up experiment required an additional 2 h.

Stimuli

Stimuli were suprathreshold sinusoidal vibration frequencies between 10 and 250 Hz, chosen to activate both Pacinian and non-Pacinian mechanoreceptors. Frequency is a primary dimension of vibrotactile perception in humans (Melara & Day, 1992). Peak-to-peak vibration amplitudes ranged from 20 to 200 μm .

Vibrotactile stimuli were produced by a modified Ling vibrator (Ling Dynamic Systems, Model V203) mounted for stability on a massive 4-in.-diameter vertical steel column. A similar device has been described in detail elsewhere (Alloway & Burton, 1991; Alloway, Sinclair, & Burton, 1988). A small rod attached to the moving armature of the vibrator ended in a 3.5-mm-diameter circular tip (made of Delrin), flattened with beveled edges, that directly contacted the skin. An optical transducer monitored displacement of the rod with a resolution of less than 5 μm . A microcomputer (IBM PC) and a commercial software package (DataWave, Inc., Longmont, CO) controlled stimulation. Data on displacement amplitudes of the probe tip were collected by the computer and stored for calibration.

Vibratory displacement amplitude was feedback regulated and independent of load.

Pink noise (Model PN2 audio noise source, Gold Line, West Redding, CT) delivered through earphones masked potential auditory cues generated by the vibrator. A drape prevented view of the stimulator and eliminated clues related to visual motion of the probe tip.

The subjects had no experience with vibrotactile discriminations before participating in the study. An initial training session familiarized the subjects with the equipment, range of stimuli, and the discrimination tasks.

Procedure

Stimuli were applied to the distal pad of the index finger of the preferred hand. The dorsal surface of the stimulated finger rested on a plastic support consisting of a concave splint rounded on the distal end to conform to the contour of the fingernail. A plastic ring (~3 cm wide) covered the middle phalanx and reduced passive spread of vibration beyond the distal segment of the finger (Gescheider, Capraro, Frisina, Hamer, & Verrillo, 1978; Verrillo, 1962). The probe was indented ~1 mm into the exposed ventral pad of the distal fingertip. Automatic stimulus feedback control ensured consistent sine-wave amplitudes over a wide range of skin indentations. Another plastic ring provided support for the thumb and aided in stabilizing finger position. The subjects were instructed to maintain finger placement within a trial and to exert no active force against the stimulus probe. The forearm rested comfortably on a cushioned support. Two fingers of the other hand operated response buttons. The subjects initiated trials under computer control (see Figure 1). A red cue light (ready light) prompted the subject to press and release either of two buttons (Micro Switch). This triggered illumination of a yellow cue light (subject light) followed after 500 msec by a 1-sec vibrotactile stimulus, the sample (Interval 1). After a variable delay period, another 1-sec stimulus was presented for comparison (Interval 2). Thus, each trial consisted of two intervals of stimulation separated by a delay. When the second stimulus ended, a green cue light (choice light) prompted the subject to press one of the buttons, resulting in a two-alternative forced choice. The differential meaning of the two buttons depended on the tasks described below. A minimum of 2 sec

Figure 1. A schematic showing timing of events on each frequency discrimination trial. After the computer activated the ready light, the subject initiated a trial by pressing and releasing (neutral) either of two buttons (micro switch). The subject light indicated impending stimulation. On each trial, 1-sec vibrotactile stimuli were presented in two intervals separated by variable duration delay periods. After stimulation, the choice light prompted the subjects to respond by pushing one of the buttons. The meaning of the buttons depended on the experiment (see text). In some stages of the experiment, a reward click or error buzz was delivered after a correct response or an error, respectively. A minimum of 2 sec separated trials.

intervened between trials. Choice tallies and reaction times were recorded as dependent variables. Reaction time was computed as the interval from the point of choice-light illumination until closure of either button by the subject. The subjects were instructed to respond as "quickly and as accurately" as possible. They were unaware that reaction time was measured.

Analysis

Repeated measures analyses of variance (ANOVAs), post hoc Tukey tests, linear regressions, and Pearson product-moment correlations assessed treatment effects for percent correct and d' . Choice tally of Interval 1 when the higher frequency was presented in the first (hit rate) or second (false-alarm rate) interval served as the raw scores for computation of d' and beta (Boice & Gardner, 1988; Darian-Smith, Davidson, & Johnson, 1980; Green & Swets, 1966; Lamb, 1983; McFadden, 1970; Pastore & Sheirer, 1974). Time-order error, a measure of presentation-order effects, was computed after the method described by Jamieson and Petrusic (1975b) for pair comparison tasks (see Experiment 2).

EXPERIMENT 1

Frequency Discrimination Functions

In pilot studies, performance decremented as a function of delay duration most clearly when discriminations were moderately difficult with no delay between stimulus pairs. In Experiment 1, performance levels were obtained for each subject over a range of frequencies and frequency differences to identify moderately discriminable frequency pairs. However, the perceived intensity of vibrotactile stimuli of equal amplitude differs with frequency and can provide discrimination cues (Goff, 1967). Therefore, vibrotactile stimuli were first equated for intensity.

Method

In the first 1-h session, an equal subjective-intensity function was determined for each subject by a modified method of limits (Goff, 1967; Sidowski, 1966; Verrillo, 1970; Woodworth & Schlosberg, 1954). The subjects matched the intensity of vibratory stimuli of 25, 50, 75, and 250 Hz to a 100-Hz standard presented at a peak-to-peak amplitude of 30 μm (comfortably above detection threshold) (Goff, 1967; LaMotte & Mountcastle, 1975). Vibrotactile stimuli were presented in pairs (Figure 1). The first stimulus in each pair was the standard 100-Hz vibration at 30 μm . All vibratory stimuli were presented for 1 sec, with an interstimulus period of 500 msec and a minimum intertrial period of 2 sec. The second (comparison) stimulus initially varied in amplitude either ~ 10 dB above or below the expected point of equal intensity (Goff, 1967; LaMotte & Mountcastle, 1975). After each trial, the subjects pressed one button to increase or the other button to decrease the amplitude of the comparison frequency on the next trial. A click signaled that the computer registered the choice. On a first pass for each comparison frequency, amplitudes changed from trial to trial in steps of 10 μm . Finer assessments were obtained on a second pass with 1- μm steps over a restricted range determined from Pass 1. Equal intensity with the 100-Hz standard was taken as the point at which responses stably alternated around the same amplitude for at least five trials; on interrogation, the subjects confirmed that equality had been obtained. Order of comparison frequencies and higher or lower starting amplitudes were chosen randomly for each subject. One higher and lower starting amplitude produced two equal-intensity values for each comparison frequency, which were averaged. These equal-intensity amplitudes were used in all subsequent sessions to minimize intensity cues. In all ensuing stages of Experiments 1 and 2, the subjects were instructed to base their judgments on frequency and to ignore any remaining differences in intensity between vibrotactile stimuli.

In the second stage of Experiment 1, six pairs of stimuli separated by 500 msec were presented to determine performance levels for a range of frequency differences. One of three standard frequencies (50, 100, and 200 Hz) appeared as one stimulus in each pair. Comparison frequencies were chosen to range in 1- to 10-Hz steps from the standards above (incremented) and below (decremented) the expected discrimination thresholds (LaMotte & Mountcastle, 1975; Mountcastle, Steinmetz, & Romo, 1990a, 1990b; Mountcastle, Talbot, Sakata, & Hyvärinen, 1969). The subjects indicated by button response (Figure 1) the interval containing the higher frequency (target) of each pair (LaMotte & Mountcastle, 1975). Feedback was provided in terms of an audible click for correct responses and a buzzer sounding for errors. Six stimulus pairs, composing a set, were presented randomly four times in each presentation order for a total of 48 presentations in each session, which required approximately 20 min. Percent correct discrimination, d' , and beta were computed for each frequency pair. Several sessions, with stimulus pairs differing progressively less in frequency, were usually needed to estimate discrimination performance as a function of frequency difference. These data were used to identify frequency pairs of moderate discrimination difficulty at shortest delay periods for use in Experiment 2.

Results

Figure 2 shows equal-intensity functions for each subject. Values on the ordinate represent amplitudes in decibels referenced to 1 μm , averaged from one starting amplitude above and below the final value, at which a frequency was judged equal in intensity to the 100-Hz standard presented at an amplitude of 30 μm . Some intersubject variability is evident. In general, the functions decreased radically between 25 and 50 Hz, and equal-intensity amplitudes were higher for frequencies below 100 Hz. Equal-intensity amplitudes obtained for 250 Hz were lower than the standard for 5 subjects and higher than the standard for 3 subjects. Equal-intensity values for frequencies used in later stages of the study that fell between those assessed here were derived by linear interpolation.

Figure 3 shows discrimination performance, averaged over all 8 subjects, as a function of frequency difference between the three standard stimuli and their correspond-

Figure 2. Experiment 1. Equal-subjective-intensity functions. Values on the ordinate represent the average amplitude (in decibels referred to 1- μm peak) at which a frequency was judged equal in intensity to the 100-Hz standard presented at a peak-to-peak amplitude of 30 μm . Each curve represents values for 1 subject. Higher amplitudes were needed to equate the intensity of lower frequencies with 100 Hz.

ing incremented (right side of Figure 3) and decremented (left side of Figure 3) comparison stimuli. In general, discrimination thresholds were lowest for comparisons (average 43 and 68 Hz) against the 50-Hz standard and for comparisons above 200 Hz. A beta of 1.07, based on overall tally from all subjects of choice of the first interval, indicated an insignificant response bias (hit rate = 0.7, false-alarm rate = 0.26, $d' = 1.18$) toward responding that the higher frequency occurred in the second stimulus interval. Thus, as expected, with no overall response bias, percent correct (Figure 3A) and d' (Figure 3B) showed similar psychometric functions. Frequency pairs yielding 80%–95% performance levels based on each subject's results were deemed moderately difficult and selected for subsequent experiments.

Discussion

In general, functions for equal subjective intensity levels were comparable to results reported in other vibrotactile discrimination studies (Goff, 1967; Verrillo, 1970; Verrillo, Fraioli, & Smith, 1969). Goff (1967), for instance, reported U-shaped equal-intensity functions, with

higher amplitudes at low (<150 Hz) and high (>400 Hz) frequencies equated to lower amplitudes in middle-frequency ranges. In the present experiment, higher amplitudes were needed to equate lower frequencies with the 100-Hz standard at 30 μ m. Verrillo et al. (1969) reported a negative slope from 100 to 200 Hz when stimuli were matched to a 250-Hz standard at 30 dB. For example, the equal-intensity amplitude for 200 Hz was <10 μ m at 30 dB, whereas Figure 2 shows that 20 μ m was the lowest amplitude for 250 Hz equated to 100 Hz at 30 dB. However, Goff (1967) reported an increase in equal-intensity amplitude above 200 Hz, relative to 100 Hz, at 35 dB above detection threshold (~80 μ m). Positive slopes seen for 3 subjects in the present experiment above 100 Hz might have resulted if the minimum equal-intensity amplitude fell between 100 and 250 Hz. One source of differences in equal-intensity functions may lie in the small step-like method of limits employed in the present experiment. In contrast, Verrillo et al. (1969) determined equal-intensity amplitudes from magnitude estimates. Goff (1967) used a method of limits more similar to that in the present experiment, but the manner of amplitude adjustment is unclear. In both of these earlier studies, unlike in the present experiment, subjects had considerable training in intensity judgments prior to assessments. Deviations from true equal-intensity amplitudes would have resulted in some over- or underestimation of equal-intensity amplitudes. However, results of Experiment 2 (see below) show that frequency discrimination performance was unaffected by even large changes in intensity.

Using 1- and 2-mm-diameter probes, Mountcastle et al. (1990a, 1990b) reported frequency discrimination thresholds considerably lower (average 5.9 Hz) than those found here (average 19.2 Hz). Although there were other methodological differences between the present experiment and these earlier studies, such as differences in probe size and shape, lowered discrimination threshold may have stemmed from extensive training of subjects in these earlier studies. Even by completion of Experiment 2, subjects had only about 15 h of experience with vibrotactile discriminations. Subjects in the earlier studies were described as having "long experience" in vibrotactile discriminations.

EXPERIMENT 2 Decay of Tactile Memory

Experiment 2 characterized frequency discrimination performance as a function of duration of delay period between pairs of vibrotactile stimuli. The effects of filling the delay period with an attention-demanding task was also examined. A consistent interval bias was found at all delay durations.

Method

Three standard frequencies, 50, 100, and 200 Hz, were paired with one higher (incremented) and one lower (decremented) comparison frequency equated for subjective intensity and differing in frequency by amounts that resulted in 80%–95% performance levels in Experiment 1. Thus, the stimulus set consisted of nine frequencies with one standard presented in each of six pairs. For each standard, com-

Figure 3. Experiment 1. Psychometric functions. Discrimination performance was assessed for frequency increments and decrements from three standard frequencies represented here by separate curves. Decrements (left) from the standards are shown as negative frequency differences; increments (right) are shown as positive frequency differences. Curves for percent correct (A) and d' (B) are roughly symmetrical about the 0 abscissa point (see text). Values shown are averaged over all subjects. Standard errors averaged 4.4%. Error bars are omitted for clarity because curves overlap at several points.

parison frequencies averaged across subjects were 50 versus 36 Hz, 50 versus 75 Hz, 100 versus 69 Hz, 100 versus 135 Hz, 200 versus 154 Hz, and 200 versus 232 Hz. Sample and comparison stimulus pairs were separated by delay periods of 0.5, 5, 15, and 30 sec. In this two-interval two-alternative forced-choice task, the subjects indicated which of the resulting two stimulus intervals contained the higher frequency. A click rewarded correct responses; a buzzer identified errors. On 50% of the trials, the higher frequency occurred first. Frequency pairs, order of presentation of higher and lower frequencies, and delay durations were completely balanced and randomized. During a session, all pairs were presented once in each order and at each delay for a total of 48 trials. Each subject completed eight sessions, each approximately 45 min and separated by 2–24 h. Percent correct and d' were computed for each session for each standard and delay duration. Reaction time was recorded for each trial (see General Method section).

Two conditions were imposed on the basic experimental paradigm. In one condition, the delay period was unfilled, and the subjects could employ any mnemonic strategy to improve performance. No mnemonic strategy was suggested. In a second, filled condition, the subjects were visually presented before each trial with a random number from 600 to 999. Immediately after presentation of the sample and during the delay period before presentation of the comparison stimulus, the subjects orally counted from this number backwards in threes. This task has been found to require considerable attention and interferes with mnemonic rehearsal of stimulus information during the delay period (Dillon & Reid, 1969; Peterson & Peterson, 1959; Wells, 1972). Filled or unfilled condition was selected for each session on a random basis with the restraint that each condition was presented four times.

Variable intensity. Three subjects received an additional 12 trials in each session, in which amplitude varied by 15% above or below the predetermined point of equal intensity. Performance on this total of 96 trials spread over eight sessions assessed use of possible remaining variations in intensity to distinguish stimuli of different frequency.

Response bias. Two male and 2 female subjects from the main experiment participated in an additional experiment to assess response bias. On half of the trials, the subjects were instructed, as in Experiment 1, to identify the interval of each pair containing the higher frequency. On the other half of the trials, the subjects identified the interval containing the lower frequency. (See, e.g., Jamieson & Petrusic, 1975b, for a more detailed description of the method.) Thus, all stimulus conditions remained constant between the two instruction conditions, but target stimuli occurred in opposite intervals for each presentation order. Higher or lower instruction conditions were presented in blocks of 30 trials, with 0.5- and 5-sec delay periods between stimulus pairs. Delay periods were unfilled. An interfering task was not used. All other procedures were identical to those of the first part of Experiment 2.

Results

An ANOVA for reaction time revealed a significant main effect for length of delay [$F(1,7) = 14.23, p < .01$] and a significant first-order interaction of delay with correct/incorrect discrimination [$F(1,7) = 9.15, p = .01$]. In Figure 4, separate curves for reaction time averaged over correct versus incorrect trials from all subjects show the source of these effects. (Vertical bars in all figures indicate 1 standard error of the mean.) Post hoc Tukey comparisons revealed that reaction time from correct trials significantly increased between delays of 0.5 and 30 sec. Slope of the reaction time function based on correct trials differed significantly from 0 (slope = 0.01 msec/sec, y intercept = 899 msec, $p = .0001$). The slope was much more shallow after 5 sec, but reaction time on correct trials continued to

Figure 4. Experiment 2. Reaction time as a function of length of delay period between stimulus pairs. On correct trials, reaction time increased dramatically from 0.5 to 5 sec and continued to increase out to 30 sec. On incorrect trials, variations across delays were not significant. Values are averaged over all subjects across all stimulus pairs. Separate curves are shown for correct and incorrect trials. In all figures, vertical bars indicate 1 standard error.

increase out to a delay period of 30 sec. Reaction times after delays of 0.5 sec were significantly ($p = .05$) lower on correct trials than on incorrect trials. Reaction time averaged over incorrect trials varied only insignificantly across delays, and the slope did not differ significantly from 0. Main effects and interactions for filled or unfilled conditions, stimulus order, and frequency of standard were not significant with reaction time as the dependent variable.

Repeated measures ANOVAs with either percent correct or d' as dependent variables showed the same significant main effects. However, there were significant interactions with percent correct as the dependent variable, most importantly between frequency and order of stimulus presentation (i.e., higher or lower frequency in first interval), which could not be included in the ANOVA model for d' .¹ For brevity, results are reported only for percent correct.

Repeated measures ANOVAs with percent correct as a dependent variable showed significant main effects for length of delay period between sample and comparison stimuli [$F(1,7) = 27.13, p = .001$] and for engagement in an interfering task [$F(1,7) = 13.7, p < .01$].

Because the subjects were inexperienced in vibrotactile discriminations, the data were examined for possible training effects by comparing overall discrimination performance across sessions. This analysis revealed no significant main effect of session and no interactions of session with delay, interference, or frequency range. Lack of performance changes as a function of relatively brief experience with vibrotactile frequency discriminations suggests that the subjects reached a plateau in proficiency from the training session and by participation in Experiment 1.

The effect of delay on percent correct differed significantly for the three standards [$F(3,21) = 4.71, p = .01$]. Also, percent correct varied with order of stimulus presentation depending on the frequency of the standard stimulus [$F(5,42) = 5.46, p < .001$]. These first-order inter-

actions complicate interpretation of the main effects for delay and filled/unfilled condition.

Figure 5C, for example, illustrates the standard $\times$ delay interaction. Data points represent averages across subjects and stimulus pairs. Discrimination performance for the 50-Hz standard remained high across all delay periods. In contrast, discrimination of the 100- and 200-Hz standards declined at delays longer than 0.5 sec. The standard $\times$ order interaction becomes apparent by comparing performance in the two presentation orders. Performance was high for discriminations in the 50-Hz range at all delays when the higher frequency occurred first (Hi-Lo, higher followed by lower, Figures 5A and 5C), but dropped to nearly chance levels at 5-sec and longer delays when the higher frequency occurred second (Lo-Hi, lower followed by higher, Figures 5B and 5D). In contrast, discrimination of the 200-Hz standard fell dramatically for the Hi-Lo order but remained high at all delay periods when stimuli were presented in reverse order (Lo-Hi; Figures 5A and 5C vs. Figures 5B and 5D). Delay functions for discriminations of the 100-Hz standard were similar in both presentation orders.

The source of a significant [$F(6,42) = 7.59, p = .0001$] second-order interaction between frequency of the standard, length of delay period, and order of stimulus presentation is shown in Table 1. Time-order error, reflecting the strength and direction of performance asymmetries associated with presentation order, was computed after the method of Jamieson and Petrusic for pair comparisons (Jamieson & Petrusic, 1975a, 1975b)² as one half the percent correct in Hi-Lo minus Lo-Hi order. Table 1 shows that time-order error generally increased as a function of length of delay period. Consistent with frequency range differences shown in Figure 5, errors were of opposite direction (or sign) for trials involving the 50-Hz (positive) and 200-Hz (negative) standards. These time-order errors were realized as relatively constant high performance across all delays for one (preferred) order, but declining performance at longer delays for the other (nonpreferred) order.

The relationship between frequency range and the presentation order of higher and lower frequencies within a trial is further clarified in Figure 6, where percent correct has been averaged across subjects and length of delay. Lower frequencies (in the 50-Hz range) were better dis-

Figure 5. Experiment 2. Discrimination performance as a function of length of delay period for each stimulus presentation order. Frequencies were presented in high-to-low (Hi-Lo; Panels A and C) or low-to-high (Lo-Hi; Panels B and D) order. Intervals were unfilled (A and B) or filled with a backwards-counting task (C and D). Discrimination of 50-Hz and 200-Hz standards varied with presentation order. Results were more dramatic in the filled condition (see text). Values are averaged over all subjects. Average standard errors were 6.6% (with a range of 6.2%–15.5%) for the filled condition and 5.6% (with a range of 5%–13.5%) for the unfilled condition.

Table 1
Time-Order Error (%) by Standard Frequency and Delay

Delay (sec)	Standard Frequency (Hz)		
	50	100	200
0.5	7.5	2.5	0.5
5	14.0	0.5	-12.5
15	8.5	-6.0	-17.0
30	14.5	-7.5	-19.5

Note—Values were averaged over all subjects and both comparison frequencies.

criminated when the higher frequency occurred first (HL). In contrast, for high frequency discriminations (in the 200-Hz range), performance was better when the higher frequency occurred second (LH). In the mid-frequency range (around 100 Hz), response asymmetries associated with stimulus order were less pronounced. The relatively smaller response asymmetry in discrimination of the 100-Hz standard in the unfilled condition (Figure 6A) resembled the pattern for 200 Hz. Discrimination of 100 Hz was equal for both orders in the filled condition (Figure 6B). As shown in Figure 5 and Table 1, these response asymmetries extended out to delay periods of 30 sec and were remarkably consistent across subjects (not shown).

The different directions of time-order errors with standard frequency (see Table 1 and Figure 6) suggested that segregating the data by preferred and nonpreferred orders would reveal the source of the significant main effects of delay and filled/unfilled condition on percent correct.

Figure 7A shows that with stimulus pairs presented in the preferred-order performance remained high across all delays (chosen preferred order was Hi-Lo for 50 Hz and Lo-Hi for 100 and 200 Hz). For this order, regression of percent correct on delay showed that the slope for the functions derived from both filled and unfilled conditions did not differ from 0. Thus, length of delay and backwards counting had no effect on discrimination performance when stimuli were presented in the preferred order. However, performance decremented with longer delays for stimuli presented in the nonpreferred order, with revealing differences between the filled and unfilled conditions (Figure 7B). With delays filled by the backwards-counting task, percent correct decreased significantly ($p < .05$) from 78% at 0.5 sec to 53% at 5 sec (slope from 0.5 to 5 sec = $-0.5\%/sec$, y intercept = 80.5% , $p < .001$). Performance remained at near-chance levels at delays from 5 to 30 sec, with the slope for this delay range not significantly different from 0. For the unfilled condition, performance also decreased significantly from 83.5% at delays of 0.5 sec to 68.9% at delays of 5 sec (slope = $-0.3\%/sec$, y intercept = 85.1% , $p = .001$). In contrast to the filled condition, performance continued to decrease at delays beyond 5 sec, but at a more gradual rate (slope from 5 to 30 sec = $-0.05\%/sec$, y intercept = 71.9% , $p < .01$) to 55% at delays of 30 sec. It should be noted that average performance at 0.5-sec delays in the filled condition was not significantly different from that in the unfilled condition, indicating that backwards counting had little effect at delays of 0.5 sec. In the

Figure 6. Experiment 2. Performance averaged across delays for each standard frequency, stimulus presentation order, and unfilled and filled condition. Interval bias varied with frequency range. (A) When delay periods were unfilled, significant interval bias was present for discriminations involving all three standards. (B) When the subjects counted backwards during delay periods, significant interval bias was seen for the 50-Hz and 200-Hz standards. Direction of bias varied with frequency range. Stars below abscissa indicate significant ($p < .05$) differences between joined means. HL, high-to-low order. LH, low-to-high order (see text for further explanation). Vertical bars indicate 1 standard error.

Figure 7. Experiment 2. Performance as a function of length of delay in filled or unfilled delay periods by preferred presentation order (see text). (A) Percent correct remained high at all delays when stimuli were presented in preferred order. (B) Stimuli presented in nonpreferred order. With filled delays, percent correct decreased to chance by 5 sec. With unfilled delays, percent correct decreased dramatically but at a slower rate by 5 sec and decremented to chance by 30 sec. Points represent averages across subjects and stimulus pairs. Vertical bars indicate 1 standard error.

filled condition, discrimination performance dropped to near-chance levels after delays of only 5 sec. In the unfilled condition, performance dropped dramatically but was significantly ($p < .05$) higher after 5 sec than in the filled condition. Above-chance performance at 15-sec unfilled delay approached a significant difference from chance. By 30 sec, discrimination performance was indistinguishable from chance in both filled and unfilled conditions. The difference in performance levels and decay rates suggests that backwards counting interfered with some mnemonic strategy employed in the unfilled condition. With rehearsal, some information about stimulus frequency persisted for over 15 sec.

Response bias. For 4 subjects, the identity of the target (higher vs. lower) stimulus was manipulated while all stimulus conditions remained the same as in the first part of Experiment 2. The subjects were instructed to identify the interval of each stimulus pair containing either the higher or the lower (target) frequency (see, e.g., Jamieson & Petrusic, 1975b). Thus, the direction of errors under the two instruction conditions will differ to the extent that presentation-order effects stem from simple response bias—

here, manifested as a button preference. A repeated measures ANOVA with percent correct as the dependent variable showed significant first-order interactions for frequency of the standard (i.e., 50, 100, 200 Hz) with stimulus presentation order [$F(5,18) = 4.48, p < .01$] and for frequency of the standard with instruction to identify interval containing higher versus lower frequency [$F(5,18) = 3.3, p < .05$].

Contrary to the hypothesis that presentation-order effects stemmed from a simple response bias, similar patterns of performance asymmetries were found in both the higher and the lower instruction condition. The performance asymmetries across the three standard frequencies clearly show that the direction of these time-order errors varied with frequency range (e.g., 50 vs. 200 Hz). Performance percentages and values of beta averaged over all subjects are given in Table 2 by standard frequency for each presentation order and instruction condition. The 50-Hz standard was better discriminated when stimulus pairs were presented in Hi-Lo order (i.e., 50 vs. 36 Hz and 75 vs. 50 Hz); the 100- and 200-Hz standards were better discriminated when stimulus pairs were presented in Lo-Hi order (i.e., 69 vs. 100 Hz, 100 vs. 135 Hz, 154 vs. 200 Hz, 200 vs. 232 Hz).³ Discrimination performance (percent correct) in each condition for each subject correlated [Pearson $r(6) = .87, p < .001$] across the higher and lower instruction conditions, indicating that the patterns of performance asymmetries replicated. Significant presentation-order differences for discriminations of 50 and 100 Hz were found when the subjects were instructed to identify the interval containing the higher frequency but not the lower frequency, thus accounting for the standard $\times$ instruction interaction.

Variable intensity. Three subjects received extra trials, in which vibration amplitude varied 15% from predetermined equal-intensity values (see Experiment 1). A repeated measures ANOVA revealed no difference in discrimination performance on equal-intensity and unequal-intensity trials, suggesting that the subjects based discriminations on frequency differences even in the presence of amplitude cues.

GENERAL DISCUSSION

Tactile Memory Demand

Measures of discrimination performance and reaction time clearly demonstrated a memory demand in this delayed vibrotactile discrimination task. Discrimination performance decreased as a function of the duration of the retention interval. Reaction times on correct trials increased with longer delay periods until, by 30 sec, reaching a level equivalent to incorrect trials. Several studies suggest that reaction times reflect increasing decision processing as the accuracy of retained information decays (but see Attention and Uncertainty section below). Gescheider and colleagues (Gescheider, Wright, & Evans, 1968; Gescheider, Wright, Weber, Kirchner, & Milligan, 1969), for instance, found that reaction time for detection of a vibrotactile stimulus varied as a function of stimulus intensity and the probability (.25 or .75) that a stimulus occurred.

Table 2
Measures of Performance and Interval Bias by Frequency
for Instructions to Identify Interval Containing Higher or Lower Frequency

	Standard Frequency (Hz)					
	50		100		200	
	HL	LH	HL	LH	HL	LH
Higher Instruction						
Percent correct	96.1	85.8	78.9	89.1	71.1	88.3
Percent interval 1 chosen	96.1	14.2	78.9	10.9	71.1	11.7
SE	1.9	5.5	5.2	3.8	3.0	3.5
Beta	0.38		1.55		1.74	
Lower Instruction						
Percent correct	88.3	83.6	78.1	85.9	64.1	88.3
Percent interval 1 chosen	11.7	83.6	21.9	85.9	35.9	88.3
SE	3.1	4.2	6.3	4.4	6.1	3.3
Beta	1.25		0.76		0.53	

Note—HL, the presentation order in which higher frequency was followed by lower frequency. LH, the presentation order in which lower frequency was followed by higher frequency. SE, standard error. In this two-interval two-alternative forced-choice task with equal interval probabilities, symmetric criterion is obtained with a Beta of 1.0, which indicates lack of response bias.

Interpreting this in terms of signal detection theory (e.g., Green & Swets, 1966), they concluded that longer decision times resulted from intensities closer to judgment criterion, the signal intensity that a subject decided was sufficiently above "noise." In an auditory detection task, Emmerich, Gray, Watson, and Tanis (1972) found that reaction time decreased as a function of response confidence. Thus, when signal probability was high and therefore criterion level low, subjects tended to make more rapid decisions. Applied to vibrotactile frequency discriminations, longer reaction times could reflect increasing uncertainty and decision processing as the memory of sensory information decays. In support of this interpretation, the subjects in the present study reported hesitation when they were in doubt of the correct choice and quick judgments when they were confident. Long reaction times at 30-sec delays were associated with chance discrimination performance in the nonpreferred direction. These same high average reaction times were obtained for incorrect choices at all delays, suggesting a guessing strategy in the absence of sensory information.

Tactile Short-Term Memory

Many studies have reported a change in the rate of memory decay similar to that reported here at about 5 sec after presentation of a sample stimulus when rehearsal was allowed (Dillon & Reid, 1969; Gilson & Baddeley, 1969; Millar, 1974; Sullivan & Turvey, 1972, 1974). The rapid decline in performance from 0.5 to 5 sec could reflect reliance on the decaying trace of sensory memory. Evidence from magnetoencephalography studies suggests that auditory sensory memory decays principally in the 5–10 sec following stimulation (e.g., Lu, Williamson, & Kaufman, 1992; Sams, Hari, Rif, & Knuutila, 1993). Comparable data are unavailable for the somatosensory system, but studies of memory for tactile stimuli show that most of the decrease in discrimination performance occurs in the 5 sec immediately after stimulation (Gilson & Bad-

deley, 1969; Heller, 1987; Sullivan & Turvey, 1972, 1974). A slower decay rate for delay periods from 5 to 30 sec suggests that discrimination during these longer interstimulus periods may be based on a different mnemonic strategy. The source of this strategy is suggested by reduced discrimination performance beyond delays of 0.5 sec when engaged in the backwards-counting task relative to when the delays are unfilled. Performance of visual, auditory, and verbal discriminations decline over seconds or minutes (see, e.g., Cowan, 1984, 1988). Similar decay functions have been sought with mixed success for tactile stimuli. For instance, Sullivan and Turvey (1972, 1974) found no decay in identification of locus of punctate stimulation beyond delays of 5 sec, whereas Gilson and Baddeley (1969), using very similar methods, showed declining performance out to 60 sec. Kiphart, Auday, and Cross (1988) found no loss of discriminability of three-dimensional game tokens over an interval of 40 sec in a *same-different* task. Similarly, Bowers, Mollenhauer, and Luxford (1990) saw consistently high discrimination performance of simple geometric objects (i.e., circles, triangles, and rectangles) over delays of up to 20 sec. Possibly, discriminations in both of these latter experiments were trivial because the objects were easily named. In a later study using Lego nonsense shapes, Kiphart, Hughes, Simmons, and Cross (1992) showed discrimination performance decrements only after 15-sec delays. However, Millar (1974) found evidence of continuing performance decrements from delays of 5 to 10 to 30 sec. Using readily discriminable three-dimensional nonsense shapes (that were therefore difficult to name), Millar varied the delay interval between a single sample and comparison stimulus. Delays were unfilled, or subjects finger-traced standard shapes, counted backwards by threes, or engaged their motor systems by nesting barrels of descending size. Compared with the interference conditions, rehearsal resulted in improved discrimination performance after delays of about 5 sec that remained high (~80%) out to 30 sec. An important finding, then, in the

present study is that, with rehearsal of stimuli presented in the nonpreferred order, discrimination performance declined significantly but more gradually beyond the 5-sec delay to chance levels by 30 sec.

Recoding

One proposed strategy for prolonging a memory is to transform or recode the sensory information into a format better suited to its representation. For instance, tactually perceived two-dimensional shapes may be visualized (Heller, 1989; Lederman, Thorne, & Jones, 1986). Sensory information may also be condensed so that less must be remembered, such as converting the absolute position of an object in space to relative body coordinates (e.g., up-down, left-right; see Millar, 1978a). In the present study, the subjects reported a variety of sensory and linguistic recoding schemes to remember vibratory frequencies during long unfilled delay periods. One interpretation is that the subjects based judgments predominantly on the more accurate but fast-fading sensory image in the first 5 sec, after which recoded information decaying at a slower rate became more reliable. The strategy employed at longer delay periods was susceptible to interference, suggesting that rehearsal may augment or preserve the condensed or recoded tactual information in a short-term-memory buffer. The sensory afterimage, if the basis of discriminations at short delays, appears unaffected by rehearsal (Gilson & Baddeley, 1969). For the unfilled condition, some subjects reported employing a verbal strategy to remember vibratory frequency over longer delays. Frequencies were coded as "low," "high," "rough," "smooth," or "ragged." The present results indicate that, in the nonpreferred presentation order, this verbal encoding was ineffective in preserving frequency information beyond 15 sec, perhaps due to the loss of resolution inherent in trying to code a larger stimulus set (i.e., nine frequencies) into a smaller number of categories (e.g., two). Perhaps because verbal strategies proved ineffective for a stimulus set of undetermined size, some subjects reported imagining during the delay how "fast," for example, the first stimulus felt. This suggests elimination of spatial and intensity information, which proportionally reduces the processing burden of any rehearsal mechanism. These coding strategies may account for higher performance levels out to 15 sec when delay periods were unfilled and suggest that the backwards-counting task interfered with these rehearsal strategies perhaps by monopolizing mnemonic resources.

Presentation-Order Effects

Performance level in many comparative judgment tasks depends on the order of successive stimuli. Stimulus range (e.g., frequency), tasks, training, and instructions interact to produce a variety of presentation-order effects for many kinds of stimuli, including line length, figure size, weight, and tone pitch (see Hellstrom, 1985 for review). Presentation-order effects have been most frequently demonstrated in discrimination threshold determinations using the method of constant stimuli (e.g., Hellstrom, 1985;

Jamieson & Petrusic, 1975a), and only recently have been shown for pair comparisons (Masin & Agostini, 1990) of the type used in the present study. Results clearly show that level of discrimination performance depended on stimulus presentation order, and the direction of bias in terms of the preferred stimulus order varied over the tested frequency range. Similar to studies using many other types of stimuli and tasks (e.g., Hellstrom, 1985), these time-order errors generally increased with length of delay period, perhaps stemming from reliance on the decaying memory for the first stimulus. Results show that these interacting effects yielded a pattern of performance asymmetries that did not stem from a simple response bias or guessing strategy.

Presentation-order effects have not previously been demonstrated for vibrotactile frequency discriminations. However, vibrotactile masking and adaptation phenomena bear marked similarities to presentation-order effects. In vibrotactile masking, a prior stimulus may substantially raise the detection threshold of a target vibration occurring up to 200 msec later (Gescheider, Bolanowski & Verrillo, 1989; Gescheider, Bolanowski, Verrillo, Arpajian, & Ryan, 1990; Gescheider, Verrillo, & Van Doren, 1982; Hamer, Verrillo, & Zwislocki, 1983; Kirman, 1986; Verrillo & Gescheider, 1977; Verrillo, Gescheider, Calman, & Van Doren, 1983). However, masking effects completely dissipate 500 msec after stimulation, the shortest delay period used in the present study, whereas observed discrimination order effects persisted for 30-sec delays. Therefore, a common mechanism would unlikely account for both vibrotactile masking and presentation-order effects. Similarly, in vibrotactile adaptation, sustained stimulation over seconds or minutes at a given frequency results in increased detection thresholds (Craig, 1972, 1974; Gescheider et al., 1969; Goble & Hollins, 1993; Hahn, 1966, 1968; Hollins, Goble, Whitsel, & Tommerdahl, 1990) and lowered amplitude and frequency discrimination thresholds for recovery periods of roughly comparable duration (Goble & Hollins, 1993, 1994). However, adaptation seems an unlikely mechanism for presentation-order effects in the present study with 1-sec stimulus durations, relatively long interstimulus intervals, and randomly ordered frequencies.

Performance remained high even out to 30-sec delays in half of the presentation orders. Equal performance levels at 0.5-sec delays in the preferred and nonpreferred orders suggest initially equal discriminability of reciprocal sequences. One might expect that performance would eventually decline with delays beyond 30 sec even for these preferred stimulus orders. Perhaps some stimuli unfavorably bias decision criterion levels (Hellstrom, 1985). For example, extremely low frequencies may bias expectation of a subsequent higher frequency, and vice versa. When contradicted, such expectancies might impair performance. Explicit manipulations of criterion level (Darian-Smith et al., 1980; Green & Swets, 1966; LaMotte & Mountcastle, 1975) might clarify the role of decision strategies in presentation-order phenomena. However, an ANOVA revealed no significant effect of order on reaction times, suggesting equal decision criterion levels.

Any theoretical explanation of vibrotactile presentation-order effects must account for reverse response asymmetries seen for high- versus low-frequency comparisons. One possibility left for future study is that this reversal stems from differential reliance on the Pacinian and non-Pacinian mechanoreceptor classes, which are sensitive to different ranges of vibrotactile frequency (Johansson & Vallbo, 1983; Mountcastle et al., 1972). Perhaps the degree of dual-channel activation could explain high discrimination performance out to 30 sec in some presentation orders. One intriguing speculation is that the inverse direction of time-order errors for low versus high frequencies serve to cancel out in the natural exploration of textures that are often composed of broadband temporal and spatial frequencies that engage both the Pacinian and non-Pacinian tactile channels.

Attention and Uncertainty

In Experiment 2, the duration of within-trial interstimulus intervals varied randomly and without warning across trials, so that the subjects did not know on each trial when to expect the second stimulus. One possibility is that surprise produced by mounting uncertainty with increasing delays lead to increased reaction times. Also, attention might vary over longer delays, so that the unexpected onset of the second stimulus leads to altered or impaired perception and consequent decreased discriminability. This explanation would predict parallel increased reaction times on correct and incorrect trials, which would be invariant with respect to surprise. Instead, reaction times increased with longer delays only on correct trials. The subjects reported increasing difficulty after long delays in recalling the first stimulus and hesitation in making a decision, rather than surprise and consequent difficulty processing the second stimulus. Possibly, the ample 1-sec stimulus durations (Verrillo, 1965) allowed sufficient time to orient to and process each stimulus. Whang, Burton, and Shulman (1991) showed evidence for preattentive processing of vibrotactile stimuli. They simultaneously applied vibrotactile stimuli to two fingertips on each hand and found that detection of the absence of an amplitude change at one site benefited from valid over invalid cuing (a pretrial tap of one finger). Detection of an amplitude increase at one site was unaffected by invalid cuing. They concluded that detection of an absence in a field of vibrotactile stimuli required attentional resources, whereas the presence of a vibrotactile stimulus was processed preattentively. Finally, evidence from the present and other studies (Gilson & Baddeley, 1969; Lu et al., 1992; Sams et al., 1993; Sullivan & Turvey, 1972, 1974) suggests that considerable sensory information persists in sensory memory for up to 5 sec following stimulation, providing an extended opportunity to muster attentional and processing resources.

Conclusions

We conclude from decay rates demonstrated in the present study that vibrotactile stimuli are suitable for neurophysiological studies of short-term memory. Results indi-

cate that presentation order could be an important factor in vibrotactile frequency discriminations. Because of the robust and replicable time-order errors, vibrotactile stimuli may prove especially useful in exploring mechanisms underlying presentation-order effects and perceptual/decision processes involved in sensory discrimination.

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NOTES

1. d' is the ratio of interval choice in each stimulus presentation order and, therefore, cannot separately assess discrimination performance in each order.
2. This measure of time-order error using both presentation orders is proportional to percent difference used in threshold determinations in which a standard frequency always appears first (Hellstrom, 1985).
3. Comparison frequencies were averaged across subjects.

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