Amplitude and period discrimination of haptic stimuli

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(Received 22 January 1997; accepted for publication 26 March 1998)

As part of a project to examine the ability of the hand to receive speech information, the present study examined subjects’ ability to discriminate finger movements along the dimensions of amplitude and period (movement duration). The movements consisted of single-cycle, sinewave movements and single-cycle, cosine movements presented to the index finger. Difference thresholds were collected using an adaptive, two-interval, temporal forced-choice procedure. Amplitudes from 6 to 19 mm were examined, and the difference thresholds ranged from 10% to 18%. The thresholds were unaffected by the period of the movement. Periods from 3000 to 111 ms (0.33–9 Hz) were examined, and thresholds ranged from 6% to 16%. The thresholds were unaffected by the amplitude of the movement. Further measurements in which period was varied in the amplitude discrimination task and amplitude was varied in the period discrimination task indicated that subjects were not using peak velocity as the basis for discrimination. These measurements were collected using a display specifically designed for the examination of haptic stimulation and capable of presenting controlled patterns of movement and vibration to the fingers. © 1998 Acoustical Society of America. [S0001-4966(98)02407-2]

PACS numbers: 43.66.Wv, 43.66.Ts [JWH]

INTRODUCTION

In determining the sensory capacity of any system, it is necessary to provide measurements of sensitivity along a number of stimulus dimensions. In haptic perception, the ability to move the fingers and to sense changes in their movement is a key aspect in the sensory and manipulative capacities of the hand. The present study examined subjects’ ability to discriminate movements along the dimensions of amplitude and period for sinusoidal finger movement. In the amplitude discrimination measurements, the task was to report which of two finger movements had a larger peak-to-peak amplitude. In the period discrimination measurements, the task was to report which of the two movements had a shorter period. These amplitude and period discrimination measurements were collected using a display specifically designed for the examination of haptic stimulation and capable of presenting controlled patterns of movement and vibration to the fingers (Eberhardt et al., 1994). The device was designed such that in contacting it, subjects had to actively follow the patterns of movement.

One of the most significant examples of the perceptual capacities of the hand is the use of the Tadoma method of speech communication. In Tadoma the human face serves as an active, haptic display from which an observer, typically a deaf–blind individual, receives speech information by monitoring haptic cues (predominately kinesthetic and tactile cues) and air flow generated during speech (Reed et al., 1985). Tadoma users place their thumb upon a talker’s lips and fan the other four fingers across the talker’s face and neck. The movements of the lips and jaw as well as vibrations resulting from the production of speech are monitored using the fingers. By means of the Tadoma method, well-trained, deaf–blind individuals can comprehend slow-to-normal rates of speech (Reed et al., 1982). The successful use of Tadoma demonstrates that the haptic system can process a considerable amount of information about movement and vibration.

In studying the perceptual capabilities of the hand, a major issue is the extent to which one chooses to impose movement on a passively receptive hand or allows the subject to actively explore the object or display. The question as to whether active versus passive presentation may improve perceptual abilities is a complicated one (Loomis and Lederman, 1986). In studies examining this issue, researchers have attempted to provide meaningful distinctions among the types of information available in tactile perception, movement perception, and haptic perception, which includes both tactile and movement perception. Gibson (1962, 1966) focused on the distinction between active and passive touch, emphasizing his belief that the processes of touch are different depending on the method by which the information is obtained. According to Gibson (1962), active touch provides a perception of, or information about, the object in the environment that is being touched, whereas passive touch produces a perception of the events occurring at the sensory surface of the skin. Katz (1989) also focused on the difference between active and passive touch and discussed the importance of active touch or motion of the hand and fingers in achieving the rich, complex perceptions that are possible through touch. Kalaska (1994) argued for the use of actively produced movements in the study of proprioceptive mechanisms citing evidence such as the modulation by active movements of both ascending proprioceptive signals and tactile signals (Chapman, 1994).

Although acknowledging that active movement is more characteristic of perceptual processing by the hand, researchers have an understandable need to provide precise stimulus control, not always possible with the unconstrained move-
ments of the hand. Therefore there are a large number of studies that have examined sensitivity to passive movements of single joints (Clark and Hörch, 1986; Hall and McCloskey, 1983; Gandevia et al., 1983) and factors affecting sensitivity such as stimulus velocity (e.g., Hall and McCloskey, 1983) or selective changes in peripheral input (Clark et al., 1983, 1979). At the other end of the active–passive continuum are studies in which active movements produced by the subject are the focus of investigation. Tasks such as movement reproduction and matching the position of two limbs provide information about the acuity of the actively engaged proprioceptive system (e.g., Lloyd and Caldwell, 1965). Still other studies have produced considerable information about the patterns of coordinated, active movements unconstrained by external stimuli (e.g., Schoner and Kelso, 1988).

In the present study we chose a middle ground in which the subject actively followed the movement of the device, but these movements were constrained. This choice was based in part on the capabilities of Tadoma users to understand speech. The face can be considered a display that requires the user to actively follow its movements, and the user’s movements are constrained to some extent by the facial movements. A potential benefit of such a display is that it may reveal perceptual abilities not seen under passive presentation. One cost of active movement on the part of the subject is a reduction of stimulus control, and the possibility that the subject’s movement may alter the movement of the display.

There have been a number of displays designed to present speech information via the skin. For the most part these displays have used arrays of stimulators applied to passive areas of skin (Weisenberger and Miller, 1987) and thus do not engage kinesthetic receptors. In a review of tactile communication of speech, Kirman (1973) pointed out that displays that present spatial patterns of stimulation to a fixed location on the skin are not taking advantage of the full information gathering potential of the hand. The spatio-temporal presentation of tactile stimulation in conjunction with the kinesthetic input that results from positional changes in the fingers provides a richer stimulation than a simple, spatial array.

To provide a more controlled source of kinesthetic and tactile stimulation and to emulate the kind of stimulation provided by the face, Tan et al. (1989) designed an artificial Tadoma system, a mechanical face. Using this display, they made a series of measurements of subjects’ sensitivity to movements generated by the face and calculated the amount of information transmitted for various combinations of movement. When using this artificial face, the hand is positioned as it would be in natural Tadoma. Difference thresholds for displacement were measured for a number of different movements, in–out movement of the upper lip, in–out movement of the lower lip, up–down movement of the lower lip, and up–down movement of the lower jaw. The maximum displacements presented were 6 mm for upper lip in–out movement, 7 mm for lower lip in–out movement, 7 mm for lower lip up–down movement, and 24 mm for jaw up–down movement. The difference threshold was determined for each type of movement presented by itself (fixed background condition) and presented in the presence of random variations in the amplitudes of the other three types of movement (roving background condition). Weber fractions were found to be much smaller in the fixed background condition (8.3%–10.6%) as compared to the roving background condition (15.1%–46.1%).

Following up on this work, Tan (1996) developed a multifinger, positional display that presents stimulation to the thumb, index, and middle fingers. Tan demonstrated that an impressive rate of information transmission is possible using both tactile and kinesthetic stimulation. Using stimuli that consisted of combinations of low-frequency, kinesthetic stimulation (2–6 Hz) as well as tactile stimulation at middle (15–44 Hz) and high frequencies (150 and 300 Hz), Tan estimated an information transfer rate of approximately 12 bits/s, a rate that is estimated to be close to the information transfer rate achieved with the use of natural Tadoma.

Rather than focusing on the perception of movements at individual finger joints (e.g., Hall and McCloskey, 1983), the emphasis in the present study is consistent with the use of the hand in Tadoma and with Gibson’s focus on the hand as a “perceptual system” for active touch. The nature of the display that was used in the present study required that subjects, as in the Tan (1996) study, actively and purposefully attempt to move with the movement of the display. In fact, their active involvement in following and monitoring the movement of the display was required for them to maintain contact with the display and to perform the task. Other than positioning the subject’s wrist and palm on top of a hand rest, the subject’s hand and fingers were not physically restrained as they followed the movement of the display. The movements produced by the observer were more complicated than single joint movements examined in many studies of kinesthesia.

A possible future use for the current display involves the presentation of motions related to the articulatory gestures associated with speech production. Using the display, representations of lip, tongue, and jaw movements or positions could be haptically monitored by a deaf or deaf–blind observer. For this reason, movement parameters for the current study were chosen to fall within the range of amplitudes and frequencies of movements associated with the articulatory gestures of speech. A number of different studies have provided measurements of jaw and lip movement resulting from very slow rates of speech to the highest repetition rate physically possible. Depending upon the articulator, the subject’s task, individual differences, and so forth, some representative values of frequencies associated with speech movement ranged from 0.8 to 8 Hz and amplitudes ranged from 0.2 to 23.3 mm (Kelso et al., 1985; Nelson et al., 1984; Ohala, 1975). In the present study, the periods of movement ranged from 3000 to 111 ms (which correspond to frequencies from 0.33 to 9 Hz) and the amplitudes ranged from 6 to 19 mm.

The current study consisted of three experiments. Measurements were made of the difference threshold for amplitude (experiment 1) and period (experiment 2) for sinusoidal finger movements. Having established the range of difference thresholds for amplitude and period, some of the cues
that subjects might use in making these discriminations were examined in experiment 3.

I. GENERAL METHODS

Similar methods and testing procedures were used in all three experiments and are described below. All subjects were undergraduates selected from a pool of subjects who were paid employees of the laboratory. All subjects were right handed.

The system used to generate the finger movements consisted of a generic 486 personal computer, custom microcontroller and servoamplifier circuits, and, as actuator, the head-positioning motor from a Micropolis 1355 hard disk drive. An arm (nominally horizontal) was mounted to the motor’s rotor. A 1.4×1.9-cm finger plate on which was glued a plastic washer was mounted to the distal arm end. This served as the finger rest. Rotor-to-plate separation was 9.4 cm. The plate moved primarily in the vertical direction, with a maximum plate displacement of about 5 cm. A positional error feedback servoamplifier was used to control the actuator. Absolute position was obtained by connecting the slider of a high-quality linear potentiometer (ETI LCP-12A-25) to the arm. As the motor moved, the potentiometer generated a feedback signal that caused deviations in the movement waveform (due to loading) to be compensated for by additional opposing force. Additional details of the construction and capabilities of the system may be found in Eberhardt et al. (1994) and Eberhardt et al. (1998).

Two standard waveforms were used, the “0-degree” and “90-degree” waveforms. The 0-degree waveform was one cycle of a sine function. The 90-degree waveform was one cycle of a sine function shifted 90 degrees in phase, a cosine function (as shown in Fig. 1). The amplitudes and periods tested are reported within each experiment.

In all experiments, the subjects participated in preliminary sessions in which they were familiarized with each task. Subjects practiced maintaining contact with and following the stimulator during its entire movement cycle. Subjects also had to learn to avoid applying excessive force on the contactor. When the force to the contactor exceeded the capacity of the feedback circuit to compensate, a light was illuminated. Subjects had little difficulty maintaining an appropriate amount of force against the display and following the contactor. As will be discussed, however, subjects could and did produce alterations in the amplitude of the movement. During the initial preliminary sessions, the subjects’ view of the contactor was unobstructed. During subsequent testing, a curtain blocked their view of the contactor and their hands. Although no obvious sounds were generated by the stimulator, subjects wore ear plugs to eliminate any possible auditory cues.

A two-alternative, temporal forced-choice paradigm was used to determine difference thresholds. This procedure was combined with a fast adaptive procedure and converged on 71% correct performance (Levitt, 1971). For example, at the beginning of an amplitude discrimination run, the comparison stimulus was set at an amplitude level that was 40% greater than the standard amplitude. The difference between the standard and comparison amplitude was then decreased following two successive correct responses and increased following one incorrect response. An amplitude reversal of the comparison stimulus took place after either of the following sequences of responses: (1) an incorrect response following two successive correct responses or (2) two successive correct responses following an incorrect response. A block of trials was completed after 14 reversals had occurred. The initial step size, that is, the magnitude of the increase or decrease in the comparison value, was set at 6% of the standard value. After the first reversal, the step size was 4% of the standard amplitude. The step size was then reduced by half after each subsequent reversal until the value was 0.5% of the standard value. Threshold was determined by averaging the comparison amplitudes of the last ten reversals in the run.

The tracking procedure for period discrimination was similar. At the beginning of a run, the period of the comparison was 29% shorter (higher in frequency) than the standard period. The period of the comparison was increased (moved closer to the standard) following two, successive correct responses and decreased (moved further from the standard) after each incorrect trial. Step size was based on the period of the movement, using the percentages listed above for amplitude discrimination.

Subjects were seated comfortably with their right arms elevated slightly and supported by an arm rest on a table in front of them. The right index finger was placed on the contactor of the stimulator. Subjects were informed that two movements separated by 600 ms would be presented to their index finger. Depending upon the task, they were instructed to respond orally “one” if the first interval contained the larger movement (or shorter period) and to respond “two” if the second interval contained the larger movement (or shorter period). For all measurements subjects were provided with a verbal description of the task, a visual illustration of the stimuli, and sample blocks of trials (continued until the subject indicated that they understood the task). Trial-by-trial feedback was provided orally.
II. EXPERIMENT 1

In experiment 1, subjects’ sensitivity to changes in amplitude of finger motion was examined. The experiment consisted of three sets of measurements with two different waveforms. The purpose was to obtain amplitude difference thresholds across a range both of amplitudes (sets 1 and 2) and of movement periods (set 3). For these measurements, two sinusoidal movements, differing in amplitude, were delivered to the right index finger (see Fig. 1). Subjects indicated which of the two movements had the larger amplitude. In sets 1 and 2, all movements were at a single period, 1000 ms. Each stimulus in the first set of measurements was one cycle of a sine function (0-degree waveform). Each stimulus in the second set was an offset cosine function (90-degree waveform, see Fig. 1). For the 0-degree waveform, the movement began at the point of maximum velocity in the sine function. Subjects commented that cues associated with the onset of movement such as velocity, acceleration, or jerk appeared to be useful in discriminating between the two movements. The higher amplitude stimulus, the comparison, always had the higher stimulus onset velocity, acceleration, and jerk. The 90-degree waveform, in which movement onset occurred at a point of minimum velocity, was examined to see whether onset characteristics affected performance. In set 3, a single amplitude of the 90-degree waveform was tested at three different periods of movement, 167, 333, and 1000 ms. With changes in period, a number of aspects of the waveform change such as peak velocity and acceleration. The purpose of set 3 was to determine whether sensitivity to amplitude differences remained constant across a range of periods.

A. Methods

Six subjects were tested in the first set of measurements, five in the second set of measurements, and five in the third set of measurements. Subjects were selected on the basis of availability, so that some subjects participated in more than one set of measurements. Table I shows the stimuli used in all three sets. For example, in the amplitude discrimination task of set 1, three standard amplitudes (6.3, 11.8, 19.2) were tested at a period of 1000 ms (1 Hz) using the 0-degree waveform. Due to a calibration error, the size of the two larger standard amplitudes was 0.1 mm larger for the 90-degree waveform compared to the 0-degree waveform.

For sets 1 and 2, each testing session consisted of two to three blocks of trials. Subjects completed six blocks of trials at each standard amplitude for the 0-degree waveform and four blocks of trials at each standard for the 90-degree waveform. The order of presentation varied randomly with the restriction that all three amplitudes of movement had to be presented before one of them was presented again. In set 3, each testing session consisted of two to three blocks of trials, and subjects completed seven blocks of trials at each period of movement. The order of presentation varied randomly with the restriction that all three periods of movement had to be presented before one of them was presented again.

B. Results

The results are reported both as the absolute difference between the amplitude of the standard and comparison, the difference threshold (DL), and as the relative change in amplitude (Weber fraction). The Weber fraction was calculated by dividing the DL by the standard amplitude and multiplying this value by 100 to obtain the percentage change. The upper function in Fig. 2 shows the DL for the 6.3-, 11.8-, and 19.2-mm standards from set 1. It appears that the DL increases at each successive increase in the amplitude of the standard. As would be expected from the set 1 data in Fig. 2, a two-way, repeated measures analysis of variance (amplitude×block) revealed a main effect of amplitude $[F(2,10) = 13.35, p < 0.01]$. No practice effect was found.

The results of the second set of measurements (90-degree waveform) are shown as the lower function in the upper panel of Fig. 2. The results are very similar to the 0-degree results. A two-way repeated measures analysis of variance (amplitude×block) revealed a main effect of amplitude $[F(2,8) = 27.43, p < 0.001]$. Although there was no overall effect of practice, an amplitude by block interaction reflected an improvement in the last two blocks of trials at the 19.3-mm standard $[F(6,24) = 2.66, p < 0.05]$.

The fact that the absolute difference in amplitude increases as the amplitude of the standard increases suggests that subjects may be discriminating relative rather than absolute changes in amplitude. Therefore the data were replotted in the lower panel of Fig. 2 with the difference between the standard and comparison amplitudes shown as the percentage change from the standard amplitude (Weber fraction). The Weber fraction also varied as a function of amplitude, decreasing as amplitude increases. For the set 1 data, a two-way repeated measures analysis of variance

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Discrimination</th>
<th>Amplitude (mm)</th>
<th>Period (ms)</th>
<th>Waveform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>amplitude</td>
<td>6.3, 11.8, 19.2</td>
<td>1000</td>
<td>0-degree</td>
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<tr>
<td>Set 2</td>
<td>amplitude</td>
<td>6.3, 11.8, 19.2</td>
<td>1000</td>
<td>90-degree</td>
</tr>
<tr>
<td>Set 3</td>
<td>amplitude</td>
<td>11.9</td>
<td>1000, 333, 167</td>
<td>90-degree</td>
</tr>
</tbody>
</table>

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<thead>
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<th>EXPERIMENT 2</th>
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<tr>
<td>Set 1</td>
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<tr>
<td>Set 2</td>
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<tr>
<td>Set 3</td>
</tr>
<tr>
<td>Set 4</td>
</tr>
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**TABLE I. Stimulus conditions for the main sets of measurements in experiments 1 and 2.**

The results demonstrate that subjects are able to discriminate the amplitude of actively followed movement. The range of Weber fractions across subjects and across the three standard amplitudes and across the two waveforms was 17% with a low of 5% and a high of 22%. The individual subjects in the Tan et al. (1989) study showed a smaller range of Weber fractions (6.1%) across subjects and across displacements with a low of 5.5% and a high of 11.6%. Tan et al. also reported that the Weber fraction (calculated as the displacement amplitude divided by the reference amplitude) was "roughly independent" of the reference displacement. Unlike their conclusion, we did not find that Weber fractions remained constant across the standard displacements. This discrepancy, however, might be accounted for by differences between the two mechanical displays, as well as the technique used to determine threshold.

Nominal (intended) amplitudes were calculated based on displacement with a 7-g, static load placed upon the contactor of the stimulator to simulate finger load. If subjects resisted the device, they could deform and reduce the amplitude of the movement. Subjects' resistance to the movement would vary the pressure exerted against their fingerpads, as well as the actual excursion of the fingerpad. To evaluate the degree that subjects altered the nominal amplitude of the movement, the feedback signal was digitized for each stimulus presentation of the 90-degree waveform in set 2. This servocontrol feedback data provided a measure of the actual excursions of the finger that were then compared to the nominal excursion.

This analysis indicated that subjects' interactions with the display added variations in the amplitude to the nominal amplitude. At smaller nominal amplitudes, this variation was proportionally larger relative to the standard as compared to the variation at the larger standard amplitudes. This proportionally larger variation may adversely affect performance to a greater extent at the smaller as compared to the larger standard amplitudes. This variation, added by the subjects, may have contributed to the rise in the Weber fraction as the standard amplitude decreased. This interpretation is consistent with the data shown in the lower panel of Fig. 2, where percent change is greater for smaller amplitudes and declines with increasing amplitude. Also, considering the addition of subject-generated "noise" to the stimuli, the present results provide a conservative estimate of the subjects' discrimination ability. If the amount of variability added by the subject were reduced, perhaps through extensive practice or greater resistance to positional change in the contactor, and active following was still maintained, then lower thresholds for movement may be found.

The direct comparison of the 90-degree and 0-degree waveforms using 11.9-mm, 1000-ms period movements (amplitude×block) revealed a main effect of standard amplitude \( F(2,10) = 9.60, p < 0.01 \). The set 2 data are shown as the lower function in Fig. 2. Similar to the set 1 results, a two-way repeated measures analysis of variance revealed a main effect of amplitude \( F(2,8) = 24.66, p < 0.001 \).

The difference between performance for the 0-degree and 90-degree waveforms suggests that the DL and Weber fraction may be smaller for the 90-degree waveform. However, because of subject differences and the slight difference in amplitude between 90-degree and 0-degree data sets, an additional set of measurements was conducted to compare directly performance on the two waveforms. A single, standard amplitude (11.9 mm, 1 Hz) was tested with both waveforms. Five subjects completed eight blocks of trials for each waveform. A two-way, repeated measures analysis of variance (waveform×block) showed a main effect of waveform \( F(1,4) = 39.02, p < 0.01 \). The DL and Weber fraction were larger for the 0-degree waveform (2.2 mm or 18.3%) than the 90-degree waveform (1.3 mm or 11.2%). These values can be compared to the standard amplitude of 11.9 mm shown in Fig. 2.

In set 3, the Weber fractions for the 1000-, 333-, and 167-ms periods were 12.9%, 11.8%, and 12.6%, respectively. The corresponding DLs were 1.53, 1.39, and 1.45 mm. The repeated measures analysis of variance (period×block) on either the Weber fraction or the DL showed no main effect of either period \( F(2,8) = 0.97, p > 0.05 \) or block \( F(6,24) = 0.62, p > 0.05 \).

C. Discussion

The direct comparison of the 90-degree and 0-degree waveforms of experiment 1 as a function of the standard amplitude. The main effect of amplitude as the lower function in Fig. 2. Similar to the set 1 results, a two-way, repeated measures analysis of variance revealed a main effect of standard amplitude of 11.9 mm shown in Fig. 2. The repeated measures analysis of variance (period×block) on either the Weber fraction or the DL showed no main effect of either period \( F(2,8) = 0.97, p > 0.05 \) or block \( F(6,24) = 0.62, p > 0.05 \).

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demonstrated that the DL was greater for the 0-degree as compared to the 90-degree waveform. All subjects showed higher average thresholds for the 0-degree waveform as compared to the 90-degree waveform. This result, which is in the opposite direction to that suggested by the subjects’ comments, indicates that cues associated with onset may be potent stimuli, but may in fact, be detrimental to performance. Although testing at a wider range of amplitudes and frequencies is needed before a firm conclusion can be drawn, the present data offer no evidence that onset cues aid discrimination. As noted in the previous paragraph, subjects’ interactions with the display added variations in amplitude to the nominal amplitude. An interesting possibility, not explored in the current measurements, is that differences in performance between the 0-degree and 90-degree waveforms might be related to differential interactions with the display.

The amplitude discrimination results of set 3 showed that across the three periods of movement tested (1000, 333, 167 ms) sensitivity to changes in amplitude was independent of the period of movement. Rabinowitz (1993), testing a substantially larger range of frequencies (2–32 Hz), did report a slight decrease in the JND for amplitude discrimination with increasing frequency. In the present study changing the period from 1000 to 167 ms changes a number of cues that could affect sensitivity, such as peak velocity or acceleration, however, the DLs remained unchanged. However, it is possible that if we had tested over a larger range of periods, a decrease in the DL may have been found.

III. EXPERIMENT 2

In experiment 2 measurements were made of the DLs for period in a manner that paralleled the amplitude measurements in experiment 1. The purpose was to obtain period DLs across a range of periods (sets 1, 2, and 3), to obtain DLs across different amplitudes (set 4), and to determine whether period DLs were affected by variations in movement duration (set 5). Table I shows the stimuli used in the first four sets of measurements. In all measurements, two sinusoidal movements differing in period were delivered sequentially to the right index finger. Subjects indicated which interval they perceived to contain the shorter period of movement. As in experiment 1, two types of sinusoidal movement were presented, 0-degree (sets 1 and 2) and 90-degree (sets 3, 4, and 5). The five sets of measurements differed in the periods of the standard movements tested. In sets 1, 2, and 3 all measurements were made at a single amplitude of movement (11.9 mm). Set 4 differed from the other three sets in that a single standard period (1000 ms) was tested at two different amplitudes of movement (6.3 and 11.9 mm). With changes in amplitude, a number of aspects of the waveform change, such as peak velocity and acceleration. The purpose of set 4 was to determine whether sensitivity to period differences remained constant across different amplitudes. In a fifth set of measurements the overall duration of movement was varied to determine whether sensitivity to period differences was impaired by irrelevant variations in movement duration. In these measurements, the duration of one of the movements was lengthened randomly by increments of up to 400 ms producing a movement composed of more than a single cycle, but less than two complete cycles and thus separating period from overall duration.

A. Methods

Six subjects participated in the first set of measurements, five in the second, five in the third, five in the fourth, and six in the fifth. Subjects were selected on the basis of their availability, so that some participated in more than one of the five sets of measurements. The subjects’ task was to select the temporal interval that contained the shorter-period movement. Subjects were instructed to respond “one” if the first interval contained the shorter-period movement or “two” if the second interval contained the shorter-period movement. Testing sessions consisted of two to three blocks of trials. In sets 1, 2, and 3, each standard period had to be tested before one of them could be presented again. In set 4, the two amplitudes were tested on alternating blocks of trials. The number of measurements completed at each standard period in sets 1, 2, and 3 were six, six, and five, respectively. In set 4, 15 blocks of trials were completed at each amplitude of movement.

In set 5, the overall duration of movement was changed on a random basis to examine the extent to which the DL for period was affected. Two 11.9-mm, 90-degree movements were presented on each trial. The standard period was 1000 ms. Two duration conditions, the “single” and the “delta t” conditions, were tested. The single condition was identical to the procedure described in the first four sets of measurements reported above, that is, each movement consisted of a single cycle of the 90-degree waveform. In the delta t condition, the duration of either the comparison or the standard movement was incremented by 100, 200, or 400 ms producing a movement that was longer than a single cycle but less than two complete cycles. The time increment was always added to the second interval of movement, and the placement of the standard and comparison was varied on a trial-to-trial basis such that the duration of the comparison was longer on approximately half of the trials and the duration of the standard was longer on the remaining trials. The three time increments were presented randomly on a trial-by-trial basis. Subjects were informed that an additional increment of time would be added to one of the two movements on each trial. They were instructed to respond with the interval containing the shorter period movement and ignore overall duration. After the subject responded, feedback was provided and the contactor was returned to the original starting position. Six subjects completed ten blocks of trials for each condition.

B. Results

All of the reported DLs (absolute differences in period between the standard and comparison) and Weber fractions (relative differences in period calculated by dividing the DL by the standard period and multiplying by 100 to get the percent change) are based on the movement’s period. The DLs for each standard period in set 1 are shown in Fig. 3. The results of an analysis of variance were consistent with the trend shown for the set 1 data, that is, discriminability declined with increasing period. A two-way, repeated mea-
showed a significant overall effect of the standard period, but a post hoc analysis (Tukey HSD) found no significant difference between the Weber fractions for the 1000- and 333-ms standard periods.

In set 4, the Weber fractions for the 6.3-mm and 11.9-mm movements were 9.4% and 8.0%, respectively. The corresponding DLs were 94 and 80 ms. A repeated measures analysis of variance (amplitude×block) did not show a main effect of amplitude [F(1,4)=6.13, p>0.05] or block [F(2,14)=1.10, p>0.05]. There was, however, an amplitude by block interaction [F(14,56)=1.94, p<0.05]. The Weber fraction for the 11.9-mm amplitude was consistent with the measurements in data sets 1, 2, and 3.

For set 5, the Weber fraction (and DL) in the single period condition was 7.4% (74 ms) and in the delta t condition was 8.6% (86 ms). A repeated measures analysis of variance (condition×block) showed no significant effect of condition [F(9,45)=0.91, p>0.05]. It should be noted that these measurements do not rule out the use of overall duration in the previous single-cycle measurements (sets 1–4) in which the overall duration and period were identical. These results suggest that when overall duration and period are not identical (set 5) subjects do not have to rely solely upon overall duration as a cue in this particular period discrimination task. These measurements do not, however, eliminate the possible use of temporal cues other than the overall duration such as the period of the movement or the time it takes for the finger to move from its highest to its lowest point.

C. Discussion

For the discrimination measure common to all three sets of data (the 333-ms standard), the Weber fractions were within 1% of each other. For the 1000-ms standard, tested in set 1 (0-degree), set 3 (90-degree), and set 4 (90-degree) performance was within 4%. The data suggest that performance on the period discrimination task is not greatly affected by the phase of the wave. The Weber fractions measured here tended to increase as the period became shorter. Rabinowitz (1993) reported that the Weber fraction (delta f/ff) was “roughly 0.1” at frequencies of 4 and 8 Hz. Within the range common to the measurements of Rabinowitz, the current difference thresholds are quite similar. Although Rabinowitz did not find a change in the Weber fraction up to 8 Hz, it is possible that at higher frequencies the Weber fraction may rise, as it did at the 111-ms period (9 Hz) movement in the current measurements.

Measured as the DL, performance was poorer at the longer periods and improved with the shorter periods. The largest absolute change in period was required for the 3000-ms standard, where the DL was more than 310 ms. The amount of time required to complete a single trial at this standard period was 6600 ms. After the delivery of the movement in the first temporal interval, subjects had to wait longer for the second movement to reach completion compared to the amount of time required for the shorter period standards. It is possible that the memory requirements for this longer stimulus trial played a role in the lower performance level.
The results of set 4 showed that across the two amplitudes tested, 6.3 and 11.9 mm, sensitivity to changes in period was independent of amplitude. Whereas changes in amplitude produce corresponding changes in the peak velocity and acceleration of both the standard and the comparison, sensitivity remains unchanged.

There are a number of cues that subjects might be using to discriminate between the two periods of movement. Overall duration of movement is an obvious one. The literature on the perception of temporal intervals has shown that the difference threshold for two time intervals varies considerably based on the nature of the task, the instructions given to the subject, and the type of stimulus occurring within the time interval (Woodrow, 1951). The values for difference thresholds for time perception, however, are in the range of the DLs for period discrimination results in the present study (Woodrow, 1951). If subjects were using the duration of movement in each interval as the basis for discriminations, they were being very effective, that is, their performance was at the lower end of the values reported by Woodrow (1951) (7%–14%). In addition, subjects were making these discriminations under conditions in which the onsets and offsets of the movement interval were either abrupt (0-degree waveform) or gradual (90-degree waveform). Subjects performed the task well, even under the less than ideal conditions (i.e., the less clear temporal boundaries) presented by the 90-degree waveform.

An additional possibility is that subjects were making a judgment of perceived intensity. It was noted informally that, at a given amplitude, short-period movements were perceived as “stronger” than long-period movements when period differences were large. If subjects were sensitive to smaller differences in perceived intensity produced by period differences of the magnitude used here, it is possible that subjects were discriminating movements on the basis of perceived intensity.

**IV. EXPERIMENT 3**

Experiment 3 examined some possible cues that subjects might use in discriminating differences in amplitude and differences in period. The purpose of these measurements was to determine whether amplitude DLs are increased by irrelevant variations in the period of movement and the accompanying irrelevant changes in velocity (set 1), and to determine whether period difference thresholds are increased by irrelevant variations in amplitude and the accompanying irrelevant changes in velocity (set 2). Several stimulus dimensions vary directly with the amplitude and period of a sinusoidal motion. For example, peak velocity, peak acceleration, and average acceleration increase with increasing amplitude. For the sake of simplicity, all of these potential cues will be referred to as velocity cues. During the amplitude discrimination measurements of experiment 1, subjects commented that they sometimes correctly selected the comparison stimulus because it was the one that moved faster. If velocity cues were the sole or even the main cue in discriminating amplitude, then reducing the effectiveness of these cues should reduce performance.

Set 1 examined amplitude discrimination and set 2 examined period discrimination. To reduce the effectiveness of velocity cues in the amplitude discrimination task, the amplitude differences were presented via two periods of movement. On half of the trials, the standard was presented at a period of 1000 ms (1 Hz) and the comparison was presented at a period of 500 ms (2 Hz). On the remaining trials, the standard was presented at 500 ms and the comparison was presented at 1000 ms. On each trial, the periods of the standard and comparison motions were determined randomly, so that period itself was an unreliable cue for the difference in amplitude. The movement presented at the shorter period had a higher peak velocity and peak acceleration, that is, unless the longer period movement was large enough in amplitude to compensate for the velocity differences resulting from the difference in period. On the trials in which the comparison (larger amplitude movement) was presented at 500 ms and the standard (smaller amplitude movement) was presented at 1000 ms, the comparison movement should always have a higher peak velocity and peak acceleration. If subjects based their decision on peak velocity or acceleration, they would be correct on these trials. On the remaining half of the trials, in which the standard was presented at the shorter period of 500 ms (2 Hz) and the comparison was presented at 1000 ms (1 Hz), the amplitude of the 1000-ms comparison would have to be twice that of the 500-ms standard for the two movements to have equivalent peak velocities. In this case, the only way a response based on velocity would be correct is if the amplitude of the 1000-ms comparison was more than twice the amplitude of the 500-ms standard. If subjects based their amplitude discrimination judgments solely on the basis of velocity cues, then the Weber fraction would have to be more than 100%.

A parallel set of measurements was carried out with a period discrimination task. In these measurements, the standard and comparison were presented at two different amplitudes. Subjects were instructed to respond to the period of the movement and ignore differences in amplitude. On each trial, the amplitude of movement in the first temporal interval was 6.3 mm and the amplitude of movement in the second interval was 11.9 mm. The comparison (shorter period movement) and the standard were randomly paired with the two amplitudes. As in the amplitude discrimination task, the effectiveness of velocity cues would be reduced since velocity varies with amplitude as well as period.

**A. Methods**

Five subjects were tested in set 1 and set 2. The stimuli for sets 1 and 2 are described in Table II. In the amplitude measurements subjects selected the temporal interval (1 or 2) that contained the larger amplitude motion regardless of the period of the motion. Two period conditions were presented. In the “same period” condition, the periods in the first and second temporal intervals were identical (1000 ms). In the “mixed period” condition, the period in the first temporal interval was 1000 ms, and the period in the second temporal interval was 500 ms. The “mixed period” condition and the “same period” condition were presented on alternate blocks of trials. The placement of the standard in the first or second
temporal interval was randomly determined on a trial-by-trial basis. Over a block of trials, the standard was presented at the shorter period on approximately half of the trials and at the longer period on the remaining half of the trials. Subjects were instructed to report the interval containing the larger amplitude movement and to ignore any difference in period. Nine blocks of trials were completed for each condition.

For the period discrimination measurements (set 2), the subjects’ task was to report the temporal interval that contained the shorter period of motion regardless of the amplitude of the motion. Two amplitude conditions were tested. In the “same amplitude” condition, the amplitude within the first and second temporal interval was identical, 6.3 mm. In the “mixed amplitude” condition, the amplitude of the motion in the first temporal interval was 6.3 mm and the amplitude of the movement in the second temporal interval was 11.9 mm. As was the case in the previous period discrimination tasks, the placement of the standard period in the first or second temporal interval was randomly determined on a trial-by-trial basis. The shorter period movement was presented at the higher amplitude on approximately half of the trials and at the lower amplitude on the remaining trials. The “mixed amplitude” condition and the “same amplitude” condition were presented on alternate blocks of trials. Seven blocks of trials were completed for each condition.

### B. Results

#### 1. Set 1

The results are presented in the first and second columns of Table III. This table shows the amplitude DLs for the “same period” and “mixed period” conditions. A two-way, repeated-measures analysis of variance (period condition×block) on the DLs showed no effect of period \(F(1,4)=1.84, p>0.05\). As expected, no significant effect of period was found when the data were reanalyzed in terms of the Weber fractions \(F(1,4)=1.84, p>0.05\). It appears there was no difference in the performance level for the “same” and “mixed” period conditions. The irrelevant variation caused no change, that is, it did not harm performance, suggesting that subjects did not have to rely on these variations to make their discriminations.

The main question this experiment was designed to address was whether velocity cues were the primary cues that subjects were using. Although velocity cues do not appear to be the major cues in amplitude discrimination, it is possible that velocity affects subjects’ responses. A more detailed analysis of the results was carried out to determine if the differences in period in the “mixed” condition had any effect on amplitude discrimination. Specifically we asked whether subjects were more likely to select the shorter period movement. This analysis showed that, although there was no change in overall sensitivity, subjects’ responding was biased by the velocity of the movement, and that they were more likely to respond with the second interval (the interval containing the shorter period). Such a response bias was not present in the “same” condition. As noted in experiment 2, movements differing in period may also differ in perceived intensity. The response bias observed here (the tendency to choose the interval containing the shorter period) is consistent with responding to the signal with the greater perceived intensity.

#### 2. Set 2

The results are shown in the third and fourth columns of Table III. This table shows the period DLs and Weber fractions for the “same amplitude” and “mixed amplitude” conditions. A two-way, repeated-measures analysis of variance (amplitude condition×block) on DLs revealed no effect of amplitude \(F(1,4)=0.18, p>0.05\). As expected, no significant effect of amplitude was found when the data were reanalyzed as Weber fractions \(F(1,4)=0.18, p>0.05\). It appears there was no difference in the performance level for the “same” and “mixed” amplitude conditions; and, as with amplitude discrimination, period discrimination appears not to depend upon velocity cues.

Paralleling the amplitude discrimination analysis in set 1, we asked whether subjects were more likely to select the higher amplitude movement in the mixed condition. Similar

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**TABLE II. Stimulus conditions for main measurements in experiment 3.**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Discrimination</th>
<th>Amplitude (mm)</th>
<th>Period (ms)</th>
<th>Waveform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
<td>amplitude</td>
<td>11.9</td>
<td>1000</td>
<td>90-degree</td>
</tr>
<tr>
<td></td>
<td>(same period)</td>
<td>11.9</td>
<td>1000/500</td>
<td>90-degree</td>
</tr>
<tr>
<td></td>
<td>amplitude</td>
<td>11.9</td>
<td>1000/500</td>
<td>90-degree</td>
</tr>
<tr>
<td></td>
<td>(mixed period)</td>
<td>11.9</td>
<td>1000</td>
<td>90-degree</td>
</tr>
<tr>
<td>Set 2</td>
<td>period</td>
<td>6.3</td>
<td>1000</td>
<td>90-degree</td>
</tr>
<tr>
<td></td>
<td>(same amplitude)</td>
<td>6.3/11.9</td>
<td>1000</td>
<td>90-degree</td>
</tr>
<tr>
<td></td>
<td>period</td>
<td>6.3</td>
<td>1000</td>
<td>90-degree</td>
</tr>
<tr>
<td></td>
<td>(mixed amplitude)</td>
<td>6.3/11.9</td>
<td>1000</td>
<td>90-degree</td>
</tr>
</tbody>
</table>

---

**TABLE III. Difference thresholds for “Same” and “Mixed” conditions in sets 1 and 2 from experiment 3.**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Amplitude discrimination at 11.9 mm</th>
<th>Period discrimination at 1000 ms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>%</td>
</tr>
<tr>
<td>Same</td>
<td>1.3</td>
<td>11.2</td>
</tr>
<tr>
<td>Mixed</td>
<td>1.7</td>
<td>14.4</td>
</tr>
</tbody>
</table>

---

Movement was presented at two different periods on each trial.

Movement was presented at two different amplitudes on each trial.
to the set 1 data, the analysis showed that, although there was no overall change in sensitivity, subjects’ responding was biased by the velocity of the movement. They were more likely to respond with the second interval (the interval containing the larger amplitude).

The results of the amplitude and period discrimination measurements of experiment 3 suggest that subjects are not basing their decision solely on velocity cues. However, the velocity cues do affect performance in that subjects are more likely to be correct on trials composed of particular amplitude and period combinations. As the data demonstrate, subjects have a tendency to take velocity cues into account, but in this particular case their influence is not large enough to alter the overall level of performance.

V. GENERAL DISCUSSION

These measurements are part of a project exploring the ability of subjects to perform discriminations of active finger movements. The goal of this project is to determine both the sensitivity of the hand to various stimulus dimensions and the cues subjects use to discriminate between stimuli along these dimensions. There are a number of stimulus dimensions that subjects might be using to discriminate period and amplitude differences. The results from experiment 3 indicate that, although velocity cues may affect the discriminability of changes in period and amplitude, they are clearly not necessary for the discriminations. Once velocity cues are excluded, potential cues in amplitude discrimination include the distance moved by the finger as well as tactile cues arising from the fingerpad’s contact with the contactor. In the period discrimination when velocity cues are eliminated, available cues include the period of the movement, tactile cues, and differences in perceived intensity.

As noted, one cue available in both the amplitude and period measurements is the tactile component of the movement. A specific tactile cue may be generated because of the way in which the contactor of the display rotates about a center axis. The movement of the finger is in a slight arc rather than a true vertical excursion. When the contactor moves upward from its horizontal resting position, the finger extends to follow the contactor and might slip very slightly. As the finger moves back to horizontal, the finger retracts slightly. The arc of the movement is such that a 14-mm excursion (measured as vertical excursion only) results in a 1-mm horizontal extension or retraction of the finger. The rate of slip would be higher for a shorter period of movement compared to a longer period of movement, and the amount of slip might correspond to the amplitude of the movement such that more slip would occur at larger amplitudes of motion. This tactile stimulation provided by the slip could provide a cue that subjects are able to use in the amplitude discrimination task (Srinivasan et al., 1990). Another tactile cue might be the pressure exerted by the contactor as it moves against the finger at the onset of the movement.

The present results indicate that subjects’ sensitivity relative to changes in amplitude and period of finger movement is similar to the differential sensitivity determined for other somatosensory stimuli. For example, the difference limen for vibratory amplitude using a two-interval, forced-choice tracking procedure varies from approximately 12% to greater than 25% for frequencies in the range of 25 to 250 Hz (Gescheidet al., 1990). In the current study, difference thresholds for amplitude were in the range of 10% to 18%. In a frequency discrimination task Rothenberg et al. (1977) presented sinusoidal vibrations varying from 20 to 225 Hz to the forearm and found Weber fractions ranging from 13% to about 26%. These values are below those found by Goff (1967) for sinusoidal stimuli presented to the fingers (20% to approximately 57%). The period discrimination values in the current study ranged from 6% to 16% for periods in the range of 3000 to 111 ms (0.33 to 9 Hz).

The results from both the amplitude and period measurements show that, with some exceptions, neither absolute nor relative sensitivity remains constant throughout the dynamic range of these stimuli. In other words, it is not possible to quote a single value for either amplitude discrimination or for period discrimination that holds for the range of stimuli one encounters in speech production. Although the present results do provide a range of values for period and amplitude discrimination, the practical consequences of a lack of any constant value for either period or amplitude discrimination is the necessity of additional measurements to determine discriminability at particular amplitude or period combinations.

The current device was designed to require subjects to actively follow the movement of the display rather than having the fingers passively moved. Although the version of the device used in the current measurements was limited somewhat in stiffness or resistance to deformation by the subject’s finger, subsequent versions have a higher degree of stiffness. Using a display that requires subjects to actively follow the movement of the stimulator may be a possible benefit for perception. Movements and muscle contractions have been shown to enhance kinesthetic acuity (Gandevia et al., 1992). Studies have also shown higher accuracy in a limb-position, matching task when the limb is actively placed (Clark and Horch, 1986). Additional information, such as that resulting from the efferent signals needed to follow along with the display movement and the monitoring of the display movement in an effort to maintain contact with it, may permit subjects to discriminate the amplitude and period of the movement better than they might during passive movement. It is also possible that the reverse would happen, that having to actively monitor and follow the display diverts attention from the discrimination task and impedes performance. Due to the design of the current display, however, it was not possible for an active versus a completely passive comparison to be performed. The current display does, however, allow the amount of resistance to be varied. Thus it will be possible to examine how changes in the resistance affect discriminability.

One potential use for a final version of the current display would be as a haptic display for the transmission of speech information. The movements presented on the display would be transformations of acoustic or physiological speech signals. The haptic cues for the speech segments may be the result of combinations of different amplitudes and frequencies of motion. For example, if the frequency or period of
jaw movement were higher for one of two segments, and the distance the jaw traveled was the same for both segments, then frequency, acceleration, velocity, and impulse would all be dimensions that might be the basis for identifying a particular segment.

VI. CONCLUSIONS

Difference thresholds for large amplitude (6.3–19.3 mm) and long-period (0.33–9 Hz) finger movements were measured. Four major conclusions from these measurements are: (1) Neither amplitude discrimination thresholds nor period discrimination thresholds were constant across the range of standards tested. Amplitude DLs ranged from 10% to 18%, and period DLs ranged from 6% to 16%. (2) In a period discrimination task, varying the duration of movement such that period and overall duration do not coincide did not increase DLs for the period of movement. (3) Amplitude DLs for an 11.9-mm standard movement did not vary significantly over a period range of 1000 to 167 ms (average DLs ranged from 11.8% to 12.9%), and period DLs for a 1000-ms standard movement did not vary significantly when tested at amplitudes of 6.3 and 11.9 mm (average DLs were 9.4% and 8.0%, respectively). (4) Amplitude DLs appear to be remarkably resistant to irrelevant variations in period and period DLs appear to be remarkably resistant to irrelevant variations in amplitude. Although performance was stable under these limited variations in the irrelevant parameters, further work is required to determine whether these conclusions would hold over a larger range of amplitudes and frequencies.

ACKNOWLEDGMENTS

The authors thank Roger P. Rhodes for his assistance in conducting these experiments. The authors also thank Silvio Eberhardt, David Coulter, John Jordan, and Yulin Chen for technical assistance. Reprint requests should be addressed to M.A. Rinker, Department of Speech and Hearing Science, 1070 Carmack Rd., Ohio State University, Columbus, OH 43210-1002 (electronic mail: rinker.13@osu.edu). This work was supported in part by research Grant No. DC-01577 from the National Institute on Deafness and Other Communication Disorders, National Institutes of Health, to the third author. The research was also supported by research Grant No. DC-00095 from the National Institute on Deafness and Other Communication Disorders, National Institutes of Health, to the second author.


