Appendix A.
Tactual and Auditory Morse Code Reception[1]

1. This manuscript has been submitted to *Perception&Psychophysics*.

Reception of Morse Code Through Motional, Vibrotactile, and Auditory Stimulation

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ABSTRACT

The potential for communication through the kinesthetic aspect of the tactual sense was examined in a series of experiments employing Morse Code signals. Experienced and inexperienced Morse Code operators were trained to identify Morse Code signals that were delivered as sequences of motional stimulation through up-down (≈10 *mm*) displacements of the fingertips. Performance on this task was compared to that obtained for both vibrotactile and acoustic presentation of Morse Code using a 200-Hz tone delivered either to the fingertip through a minishaker or diotically under headphones. For all three modalities, the ability to receive Morse Code was examined as a function of presentation rate for tasks including identification of single letter, random three-letter sequences, common words, and sentences. Equivalent word-rate measures (i.e., product of percent-correct scores and stimulus presentation rate) were nearly twice as high for auditory presentation as for vibrotactile and motional presentation. Results are compared to those obtained in other research with tactual communication devices.

INTRODUCTION

In this paper, we focus on the ability to receive information through motional stimulation (i.e., the kinesthetic sense). Our long term goals are: (1) to study the kinesthetic sense as a communication channel, (2) to compare performance through the kinesthetic sense with that through other senses, and (3) to compare the ability to receive motional stimulation with the ability to produce the same movement patterns.

Most studies of tactual communication have focused on the cutaneous / tactile sensory system (see Geldard, 1973; Kaczmarek, Webster, Bach-y-Rita, & Tompkins, 1991). In contrast, research on the kinesthetic sensory system is extremely limited (see Clark & Horch, 1986, for a review). Bliss (1961) investigated the use of the kinesthetic sense as a communication channel in experiments employing an air-driven finger stimulator that was constructed as a reverse typewriter. The stimulator consisted of eight finger rests arranged in two groups on which the user could place the fingers of both hands in a manner similar to typing on the home row. Each stimulator was capable of simulating motions corresponding to the active movements of a typist's fingers in reaching the upper and lower rows on a keyboard. In one set of experiments, 42 random triplets composed of the letters *e*, *t*, *n*, *a*, *o* and *i* were presented to eight subjects. The average information transfer was

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1.75 *bits/letter* out of a maximum possible 2.58 *bits/letter*. In another experiment, 30 symbols (the alphabet, comma, period, space, and upper case) were presented in random order with equal probability to one subject (with less than 15 hours of practice). Six sequences of 130 symbols each were delivered at a rate of 0.5 to 1.5 *letters/sec*. The subject responded verbally by naming the symbols as they were received. The information rate, computed as the multiplication of percent correct, presentation rate (*letter/sec*) and information per symbol (4.91 *bits/letter*), reached a maximum of 4.5 *bits/sec* at a presentation rate of 1.32 *letters/sec*.

In a more recent study (Eberhardt et al., 1994), a two-degree-of-freedom (up-down and front-back) finger stimulator named OMAR was developed to provide slow motion as well as vibration to a finger through a single actuator. Early experiments demonstrated that some subjects were able to judge onset asynchronies of vibration and movement with such a system.

In the present study, we investigated the ability to receive information through up-down finger motions. In order to assess communication rate, a code was needed to convert the up-down finger motions into meaningful messages. The International Morse code was chosen because it is a well-established code and its learning patterns have been well studied. Bryan & Harter (1899) followed students of telegraphy for over half a year and tested their ability to send and receive Morse code weekly. They found that while the students' ability to send the code improved monotonically, their ability to receive the code reached several plateaus and eventually exceeded that of sending. The plateaus in the reception curves were interpreted as evidence that a student of telegraphy first learned to receive individual letters, then developed the skills to receive common words as the basic units, and eventually learned to receive short phrases after many years of practice. By employing highly skilled Morse code operators as subjects in the current study, it was possible to take advantage of their previous experience in chunking coded messages. Inexperienced subjects were also trained and tested for comparison. The fact that Morse code is used to both send and receive information enables us to investigate the relationship between the ability to receive motional stimulation and the ability to produce such motions. Finally, Morse code can be adapted to many sensory modalities. Although Morse code is traditionally received through the auditory channel, hearing-impaired ham operators have put their hands on speakers to receive Morse code through the tactual channel. We compared subjects' ability to receive the Morse code through motional, vibrotactile, and auditory stimulation using common tasks.

METHODS

Morse Code is a temporal sequence of patterns in which each letter of the alphabet has its own unique pattern. Patterns consist of elements (dot = one unit = U; dash = three units = $3U$) and pauses. Morse-code reception was studied for motional, vibrotactile, and auditory stimulation as a function of presentation rate R in words per minute (*wpm*), which is related to the duration of U (in *msec*) by $R = 1200/U$. A more complete description of Morse Code is provided in the Appendix attached at the end.

Subjects

Two experienced Morse Code operators from the Boston Amateur Radio Club (subjects E1 and E2) and two inexperienced MIT students (subjects N1 and N2) participated in the experiments. E1 and E2 were both males, aged 38 and 40, and were licensed as extra-class ham radio operators. N1 was a 28-year old female and N2 an 18-year old male. Three of the subjects (E2, N1, and N2) were right-handed and one (E1) was left-handed. Except for N1, who was also the experimenter, all subjects were paid on an hourly basis.

Tasks

The reception of Morse Code through motional, vibrotactile, and auditory stimulation was studied using four tasks in the following order: single-letter identification, three-letter random-sequence identification, common-word identification, and sentence reception. Table A-1 lists the testing conditions in chronological order. All four subjects participated in each experiment except that (1) only the experienced subjects were tested with sentences (because the inexperienced subjects were unable to perform this task), and (2) the experienced subjects were not trained auditorily with the single-letter and three-letter sequences (because they were already experienced with the reception of Morse Code through auditory stimulation).

TABLE A-1. EXPERIMENTAL CONDITIONS AND ORDERING (M: MOTIONAL, V: VIBROTACTILE, A: AUDITORY)

MODE	*TASK*	*SUBJECTS*
M	1-letter	E_1, E_2, N_1, N_2
M	3-letter	E_1, E_2, N_1, N_2
M	words	E_1, E_2, N_1, N_2
M	sentences	E_1, E_2
V	1-letter	E_1, E_2
V&A interleaved	1-letter	N_1, N_2
V	3-letter	E_1, E_2
V&A interleaved	3-letter	N_1, N_2
V	words	E_1, E_2
V&A interleaved	words	N_1, N_2
V	sentences	E_1, E_2
A	sentences	E_1, E_2
A	words	E_1, E_2

Single-letter identification. On each trial, the subject was presented (through motional, vibrotactile, or auditory stimulation, as described below) with the Morse code for one of the 26 letters of the alphabet. The subject was instructed to respond with one of the 26 letters on a computer keyboard, and then trial-by-trial correct-answer feedback was provided by displaying the correct response on a computer screen. Each run consisted of 130 presentations of single letters in random order with each of the 26 letters presented exactly 5 times. The duration of each run varied from 5 to 20 min depending on the response time of the subject. Each subject started from the lowest rate of stimulus presentation and was allowed to proceed to the next higher rate only after the completion of (1) one run with a perfect score of 100%, (2) at least three runs with scores over 95% (not necessarily consecutively), or (3) roughly ten or more consecutive runs with similar scores (i.e., a clear plateau). Four rates were tested: 12, 16, 20, and 24 *wpm*, except for motional stimulation where the rate of 20 *wpm* was not used.

Three-letter identification. On each trial, the subject was presented (through motional, vibrotactile, or auditory stimulation) with the Morse code of a three-letter nonsense word (with each letter chosen randomly with equal *a priori* probabilities from the 26 letters), instructed to respond with a three-letter sequence, and then shown the correct response. The letters were separated by a pause of duration *3U*. The subject could either "copy on the fly" (i.e., the response to the first letter was entered while the second letter was being presented) or "copy behind" (i.e., the subject waited until all three letters were presented before entering the response). Each run consisted of 52 presentations of three-letter sequences in random order, such that each letter of the alphabet was presented exactly 6 times. A response was considered correct only if all three letters were identified correctly in the correct order. Each subject started from the lowest rate of stimulus presentation and was allowed to proceed to the next higher rate only after the completion of (1) one run with a perfect score of 100%, (2) three runs with scores over 90% (not necessarily consecutively), or (3) roughly ten or more consecutive runs with similar scores (i.e., a clear plateau). Four rates were tested: 12, 16, 20 and 24 *wpm*. All subjects chose the copy-behind method of responding.

Common-word identification. The material consisted of 600 words obtained from the corpus of The American Heritage Word Frequency Book (Carroll, Davies, & Richman, 1971). The selection of words was based on rate of occurrence and minimum length. All the stimuli occupy ranks between 1000 and 5300 per million and contain at least 7 letters. Two randomizations of the 600 words into twelve 50-item word lists were constructed and employed in the testing such that all lists from the first randomization were presented prior to lists from the second randomization. The subjects were told before the experiment that the test material consisted of common English words. On each trial, the subject was presented (through motional, vibrotactile, or auditory stimulation) with the Morse code of one word from a chosen list, instructed to respond by typing out a response word (either by "copying on the fly" or "copying behind"), and then shown whether the response was "right" or "wrong".[2] The letters within a word were separated by a pause of duration 3U. Each run consisted of one list (i.e., 50 words). Different rates were selected for experienced and inexperienced subjects with each of the three types of stimulation in order to obtain a wide range of percent-correct scores as a function of stimulus presentation rate. Each subject performed at least three runs per stimulus presentation rate (unless the performance was 0% or above 90%, in which case only one run was conducted), and proceeded from the lowest to the highest rate.

Sentence reception. The test material consisted of CUNY sentence lists commonly used for speech and hearing research (Boothroyd, Hanin, & Hnath, 1985). Each of the 60 lists contains 12 sentences

2. Because each word was presented again later, the subjects were not shown the correct word when a mistake was made.

arranged by topic (e.g., food, animals, weather, etc.). Each sentence in a list consists of 3 to 14 common English words and each list contains exactly 102 words. The same list was never used twice with the same subject. The difficulty levels of these sentences were estimated to be equivalent to fifth to sixth grade reading levels. Prior to the experiment, the subjects were told that the test material consisted of conversational sentences but were not informed of the topics. On each trial, the subject was presented (through motional, vibrotactile, or auditory stimulation) with the Morse code of one sentence from a chosen list, instructed to repeat the sentence verbally, and only given informal feedback (e.g., the experimenter revealed specific words in the sentence if the subject asked). Letters within a word were separated by a pause of duration 3U, and words within a sentence were separated by a pause of duration 7U. The subject could either respond "on the fly" or after the entire sentence had been presented. Each run consisted of one list (i.e., 12 sentences). At the end of a run, the experimenter counted the number of words the subject was able to repeat regardless of the ordering and ignored extra words in the response. The overall word score was computed as the number of correctly-repeated words divided by 102, the total number of words in each CUNY-sentence list. Different rates were selected for the three types of stimulation in order to obtain a wide range of percent-correct scores as a function of stimulus presentation rate. Each subject was tested with at least three lists at each rate and proceeded from the lowest to the highest rate.

During all experiments, the subject was informed of the overall percent-correct score at the end of each run. Each experimental session lasted 1 to 2 hours. Subjects were free to take breaks between runs at their own pace. The experienced subjects generally completed two sessions per week. The inexperienced subjects completed three or more sessions per week.

Instrumentation and Procedure

Motional stimulation. A device designed to move the fingertip up and down was constructed around a permanent magnet servo motor with feedback from a tachometer and an optical encoder (Fig. A-1). A Plexiglas lever was attached to the motor shaft. The subject rested the index fingertip lightly over a roller which was snug-fit into a hole on the lever. The distance from the center of the motor shaft to that of the roller was 40 *mm*. The roller served to control the point of contact and to accommodate any relative motions between the finger and the lever. The system parameters were adjusted so that the position-step response was critically damped, with a rise-time of approximately 20 *msec*.

The waveforms used to drive the motor were two-level square waves. Fig. A-2 shows the waveform for the letter "P". Each waveform started with an inter-letter pause of *3U* followed by the appropriate dot-dash pattern for that letter. For the typical arrangement of the stimulator system, a downward motion at the fingertip indicated the onset of a dot or a dash. The actual vertical displacement of the fingertip was adjusted to be ≈10 *mm*. This was found to be the largest amplitude that felt comfortable at the highest rate tested (i.e., 24 *wpm*) through preliminary experimentation. With the finger pressing lightly on the roller, the overall position of the roller (and lever) shifted downwards by 1-2 *mm*, but the relative up-down motion was otherwise unchanged.

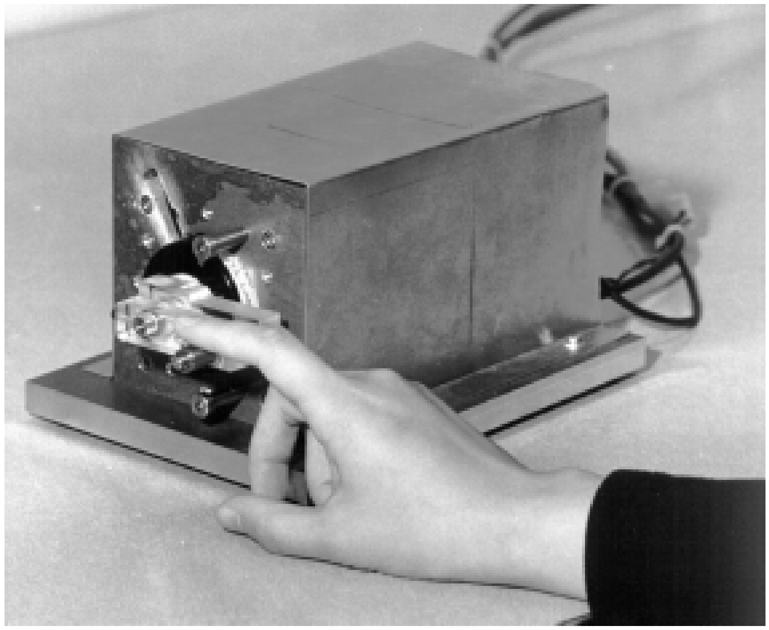

Figure A-1. The experimental apparatus. The finger is rested on a roller placed 40 *mm* from the center of the rotor. The two shoulder screws above and below the Plexiglas bars serve as the mechanical stops.

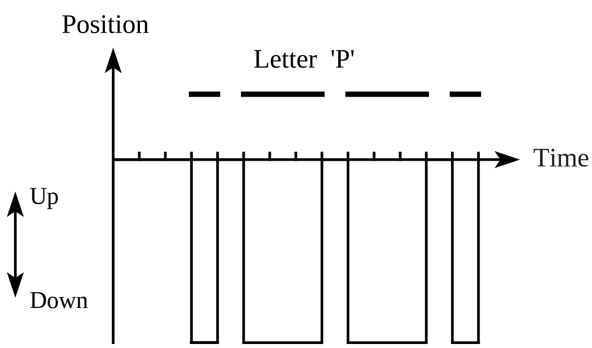

Figure A-2. Waveform used to deliver the letter "P" for motional stimulation.

The apparatus was always hidden from view. Subjects wore earphones with acoustic noise to mask any auditory cues from the apparatus. Stimuli were presented to the index finger of the dominant hand of each subject. The standard posture was to rest the fingertip lightly on top of the roller and follow the up-down motions of the roller. In general, subjects were encouraged to use a consistent posture throughout all experiments, although alternative postures were employed by some subjects under some conditions.[3] Presentation rates ranged from 4 - 24 *wpm* across the various tasks corresponding to a range in *U* from 300 - 50 *msec*. Before the experiments began, the inexperienced subjects were provided with a brief training period (averaging 3.6 *hours*) to associate letters with the movement patterns.

Vibrotactile stimulation. Stimulation was applied through an electrodynamic minishaker (Alpha-M AV-6). A 200-*Hz* sinusoidal signal gated by the square wave shown in Fig. A-2 was applied to the minishaker. The presence and the duration of the vibration indicated the presence and the duration of a dot or a dash. The subject placed the index finger of the dominant hand on the top of a flat contactor (9 *mm* in diameter) that was fit to the minishaker. The 200-*Hz* vibration was presented at a nominal level of ≈50 dB SL. Presentation rates ranged from 8-40 *wpm* across the various tasks, corresponding to a range in *U* from 150 to 30 *msec*.

During the experiments, the minishaker was placed inside a wooden box lined with sound-absorbing foam to (1) shield it visually from the subject and (2) attenuate the sound caused by the vibration. Subjects wore earphones with acoustic noise to mask any residual auditory cues from the minishaker.

Auditory stimulation. Morse-code sequences were presented diotically via headphones using the same 200-*Hz* signals that were applied to the minishaker. The presence and the duration of an auditory tone indicated the presence and the duration of a dot or a dash. For stimulus presentation rates above 56 *wpm*, a 5-*ms* Hanning window was applied to the rising and falling portion of the signals to reduce “clicks”. The subject could adjust the overall gain so that the earphone signal “felt comfortably loud”. Presentation rates ranged from 12 - 73.85 *wpm* across the various tasks, corresponding to a range in *U* of 100 - 16.25 *msec*.

Data Analysis and Reduction

For each subject, task, type of stimulation, and presentation rate, a learning curve was constructed in which the percent-correct score was plotted as a function of run number. Based on the learning curve, decisions on when to terminate were made on the basis of the criteria described for each task in the methodology section. The learning-curve data were reduced by averaging percent-correct scores (a) across the final three runs at each presentation rate, and then (b) across experienced subjects E1 and E2 and across inexperienced subjects N1 and N2.

3. Subjects were discouraged, but not prohibited, from experimenting with non-standard settings. They were asked to document all deviations from the standard setup in a log book and to discuss them with the experimenter at the end of the session. For the single-letter identification experiment, E_1 used the downward motion at the first rate of 12 *wpm*, but switched to the upward motion after starting the 16 *wpm* condition. His performance in terms of percent correct scores was measured to be about 30% higher for upward motions than for downward motions. He was thus permitted to use a set of waveforms with a polarity opposite to that shown in Fig. A-2 for all subsequent experiments. In addition, E_1 switched to a smaller range of motion (i.e., fingertip displacement was decreased to 5 *mm*) to reduce fatigue in the three-letter random-sequence identification experiment. Subject E_2 used the standard posture but preferred a larger range of motion after beginning the 24 wpm condition. After demonstrating an improvement in performance, he was permitted to decrease signal attenuation by 4 dB (i.e., fingertip displacement was increased to 15 *mm*) for all subsequent experiments.

RESULTS

Single-Letter Identification

Typical learning curves for motional stimulation are shown in Fig. A-3. The upward arrow in E2's graph indicates the time at which E2 increased the range of motion from 10 to 15 *mm* (see note 2). Apparently, the increase in movement amplitude had little effect on the overall characteristics of the learning curve at 24 *wpm*. With this simplest task and with motional stimulation, experienced and inexperienced subjects exhibit similar learning curves. As expected, both types of subjects started with lower percent-correct scores and took longer to reach performance criterion as presentation rate increased.

The percent-correct scores averaged over the last three runs for motional (M), vibrotactile (V), and auditory (A) stimulation are shown individually and in summary form in Fig. A-4. Whereas the performance of the two experienced subjects E1 and E2 was quite similar for all tests conducted, the performance of N1 was sometimes much better than that of N2. Nevertheless, averaging the data for the two inexperienced subjects does not affect our general conclusions. Therefore, in the remainder of this paper, only the summary graphs will be presented. From the summary graph in Fig. A-4, it is observed that the experienced subjects achieved the performance criterion of 95% correct at all rates tested with the motional and vibrotactile stimulation.[4] The inexperienced subjects were not able to achieve the performance criterion at rates above 16 *wpm* with motional or vibrotactile stimulation. Their performance with auditory stimulation, however, was nearly perfect at all rates tested. In general, it is clear that (1) the experienced subjects performed better than the inexperienced subjects, and (2) performance of the inexperienced subjects with auditory stimulation was better than that with motional or vibrotactile stimulation.

Three-Letter Random-Sequence Identification

The percent-correct scores averaged over the last three runs for motional (M), vibrotactile (V), and auditory (A) stimulation are shown in Fig. A-5. The experienced subjects achieved the performance criterion of 90% correct only at the lower rates of 12 and 16 *wpm* for motional and vibrotactile stimulation.[3] The inexperienced subjects were not able to achieve the performance criterion at any rate with motional stimulation and only at the slowest rate of 12 *wpm* with vibrotactile stimulation. However, their performance with auditory stimulation reached performance criterion at all rates tested. Thus, it is clear that (1) this task is more difficult than the single-letter identification task for both subject groups, (2) the experienced subjects performed better than inexperienced subjects, (3) performance of the inexperienced subjects with auditory stimulation was better than that with vibrotactile stimulation, and (4) performance with vibrotactile stimulation was better than that with motional stimulation.

4. Had the experienced subjects performed this task with auditory stimulation, they would have achieved nearly perfect scores at all rates tested.

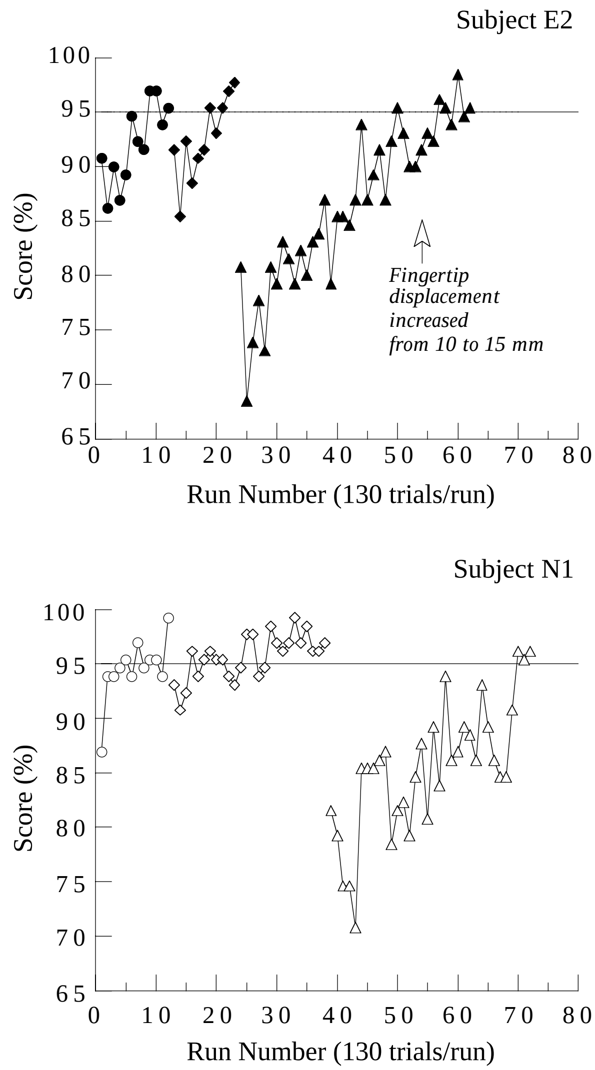

Figure A-3. Learning curves for motional stimulation from the single-letter identification test for one experienced subject (E2, filled symbols, above) and one inexperienced subject (N1, open symbols, below) at 12 *wpm* (circles), 16 *wpm* (diamonds), and 24 *wpm* (triangles). Horizontal lines indicate the performance criterion of 95%.

Common-Word Identification

This is the only task where both subject groups were tested with all three modes of stimulation. The percent-correct scores averaged over the last three runs for motional (M), vibrotactile (V), and auditory (A) stimulation are shown in Fig. A-6. Percent-correct word scores decreased with stimulus presentation rate at average rates of 5%/*wpm* (M), 5%/*wpm* (V), and 3%/*wpm* (A) for experi-

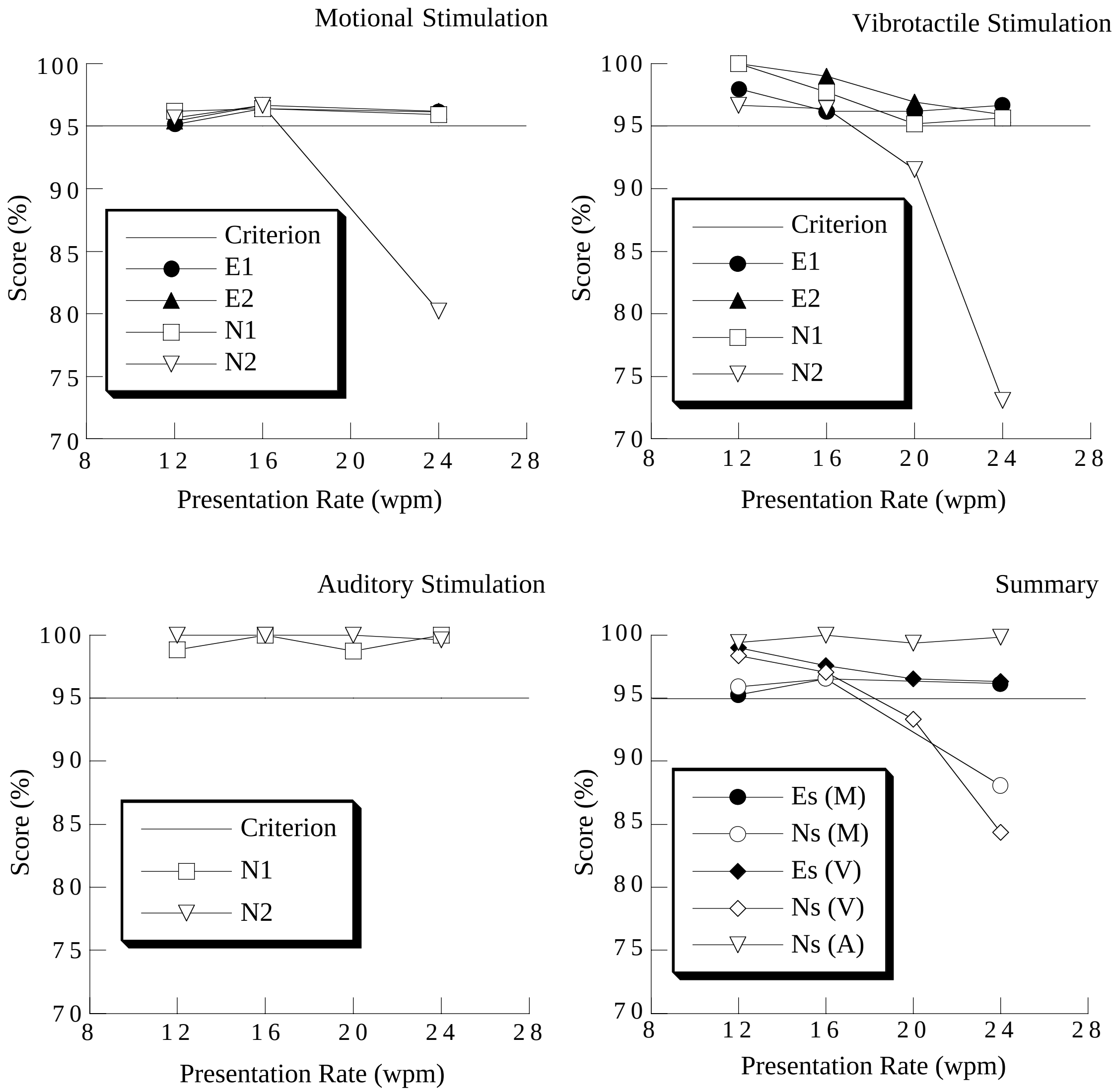

Figure A-4. Percent-correct scores averaged over final three runs from the single-letter identification test as a function of presentation rate. Individual subject results are shown in separate panels for motional, vibrotactile, and auditory stimulation. Results from each type of stimulation are summarized in the final panel by averaging across scores from the experienced subjects (Es) and from the inexperienced subjects (Ns). Horizontal lines indicate the performance criterion of 95%.

enced subjects, and 6%/*wpm* (M), 7%/*wpm* (V), and 5%/*wpm* (A) for inexperienced subjects. The presentation rates corresponding to 50% correct scores were 22 *wpm* (M), 31 *wpm* (V), and 51 *wpm* (A) for experienced subjects, and 11 *wpm* (M), 16 *wpm* (V), and 25 *wpm* (A) for inexperienced subjects.

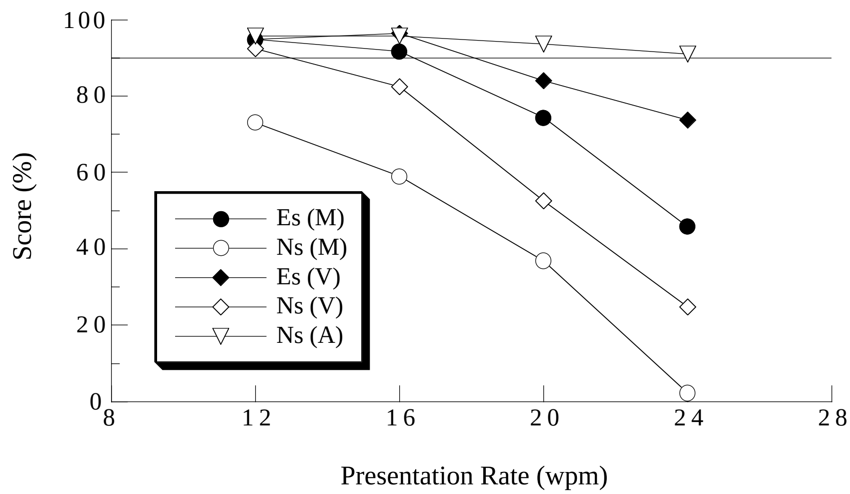

Figure A-5. Percent-correct scores averaged over final three runs from the three-letter random-sequence identification test as a function of presentation rate. Data are shown for experienced (filled symbols) and inexperienced (open symbols) subjects with motional (circles), vibrotactile (diamonds) and auditory (triangles) stimulation. Horizontal line indicates the performance criterion of 90%.

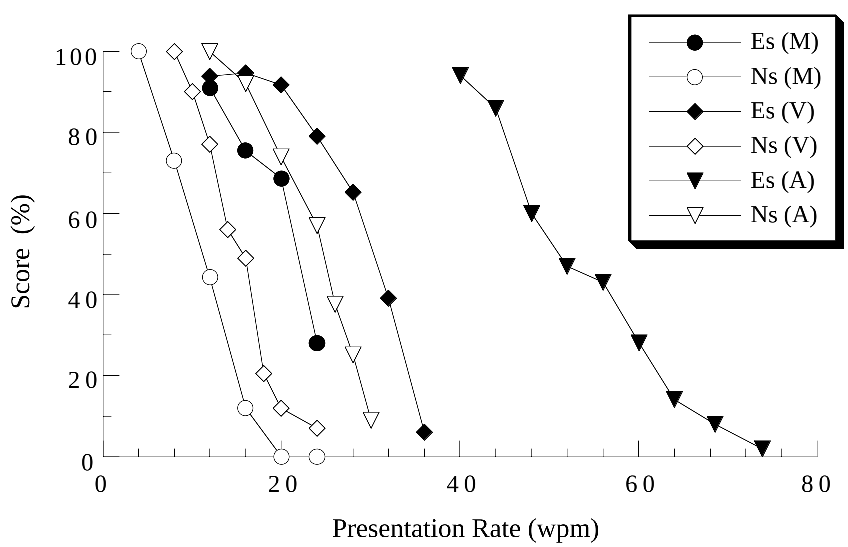

Figure A-6. Percent-correct scores averaged over final three runs from the common-word identification test as a function of presentation rate. Data are shown for experienced (filled symbols) and inexperienced (open symbols) subjects with motional (circles), vibrotactile (diamonds) and auditory (triangles) stimulation.

The results indicate that (1) in general, subjects' performance with auditory stimulation was *much* better than that with vibrotactile stimulation, which, in turn, was better than that with motional stimulation, and (2) experienced subjects performed better than inexperienced subjects with all three types of stimulation.

As another metric of performance, the equivalent word rate γ was calculated as the product of percent-correct score and stimulus presentation rate. (Cholewiak, Sherrick, & Collins, 1993, refer to this measure as the *correct words per minute*.) A maximum γ was associated with each test (see Fig. A-7). As stimulus presentation rate increased, γ increased initially, but was limited by the highest achievable γ (i.e., the presentation rate). After γ reaches the maximum, there is a trade-off between presentation rate and percent-correct scores in that γ remained at the maximum level with increasing presentation rate. After that, γ decreased as presentation rate increased. The maximum γ scores averaged across experienced subjects were 14, 19, and 38 *wpm* with motional, vibrotactile and auditory stimulation, respectively. The corresponding scores averaged across inexperienced subjects were 6, 9, and 15 *wpm*, respectively.

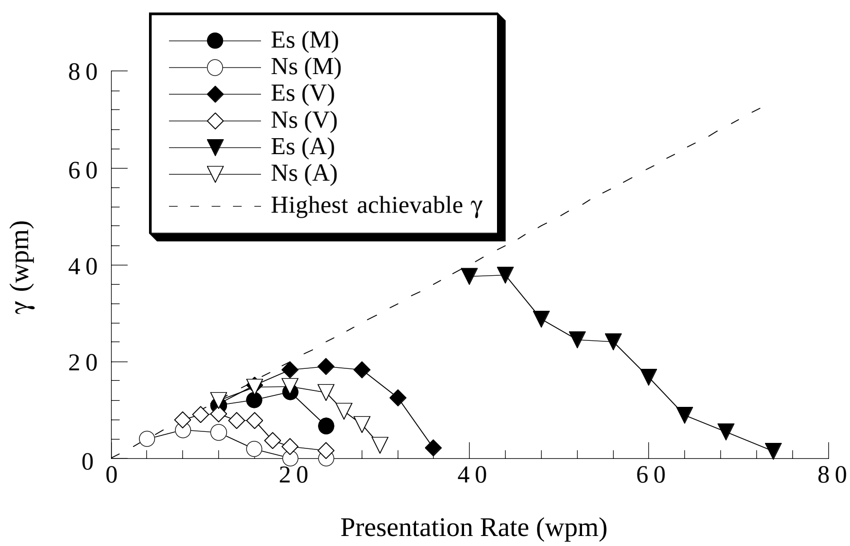

Figure A-7. Equivalent word rates γ (*wpm*) from the common-word identification test for experienced (filled symbols) and inexperienced (open symbols) subjects with motional (circles), vibrotactile (diamonds), and auditory (triangles) stimulation. Dashed line indicates the highest achievable equivalent word rate (i.e., the presentation rate).

Sentence Reception

The inexperienced subjects were unable to perform this test with any of the stimulation types; hence, only the experienced subjects were tested. The percent-correct scores averaged over the last three runs for motional (M), vibrotactile (V) and auditory (A) stimulation are shown in Fig. A-8. As stimulus presentation rate increased, performance decreased. Performance with auditory stimulation was *much* better than that with vibrotactile stimulation, which, in turn, was better than that with motional stimulation. Percent-correct word scores decreased with stimulus presentation rate at average rates of 4%/*wpm* (M), 3%/*wpm* (V), and 2%/*wpm* (A). The presentation rates corresponding to 50% correct scores were 25 *wpm* (M, extrapolated), 32 *wpm* (V), and 59 *wpm* (A). The average maximum γ scores were 18, 21, and 43 *wpm* with motional, vibrotactile, and auditory stimulation, respectively. The slightly higher γ achieved with this test compared with that achieved with the common-word identification test is probably due to the increased redundancy in the test material.

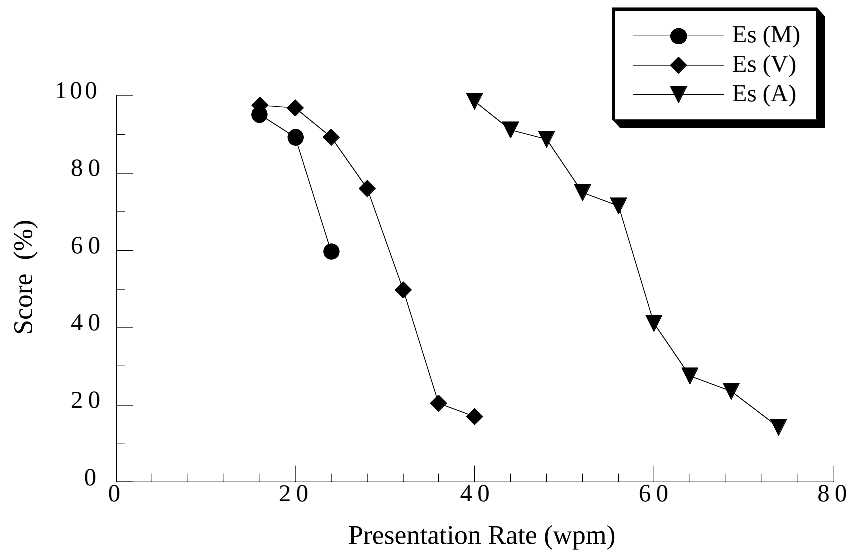

Figure A-8. Percent-correct scores averaged over final three runs from the sentence reception test as a function of presentation rate. Data averaged across the experienced subjects are shown for motional (circles), vibrotactile (diamonds), and auditory (triangles) stimulation.

DISCUSSION

We have tested experienced and inexperienced Morse code operators on their ability to receive Morse code through motional, vibrotactile, and auditory stimulation using single-letter, three-letter, common-word, and conversational-English test materials. In order to compare subjects' performance across modalities and tasks, the equivalent word rates (γ) were computed for all cases. These results are shown in Fig. A-9. The asterisks on top of the columns for the single-letter identification tests indicate that these γ values might have been higher if stimulus presentation rates over 24 *wpm* had been used. On the average, excluding data from the single-letter identification tests, the ratio of the equivalent word rates for vibrotactile stimulation to that for motional stimulation (γ_v:γ_m) was 1.2 for the experienced subjects and 1.5 for the inexperienced subjects. The ratio of the equivalent word rates for auditory stimulation to that for motional stimulation (γ_a:γ_m) was 2.6 for the experienced subjects and 2.5 for the inexperienced subjects. The ratio of the equivalent word rates for auditory stimulation to that for vibrotactile stimulation (γ_a:γ_v) was 2.2 for the experienced subjects and 1.7 for the inexperienced subjects. Overall, auditory reception of Morse code is about twice as fast as tactual (i.e., motional or vibrotactile) reception of the code for both subject groups.

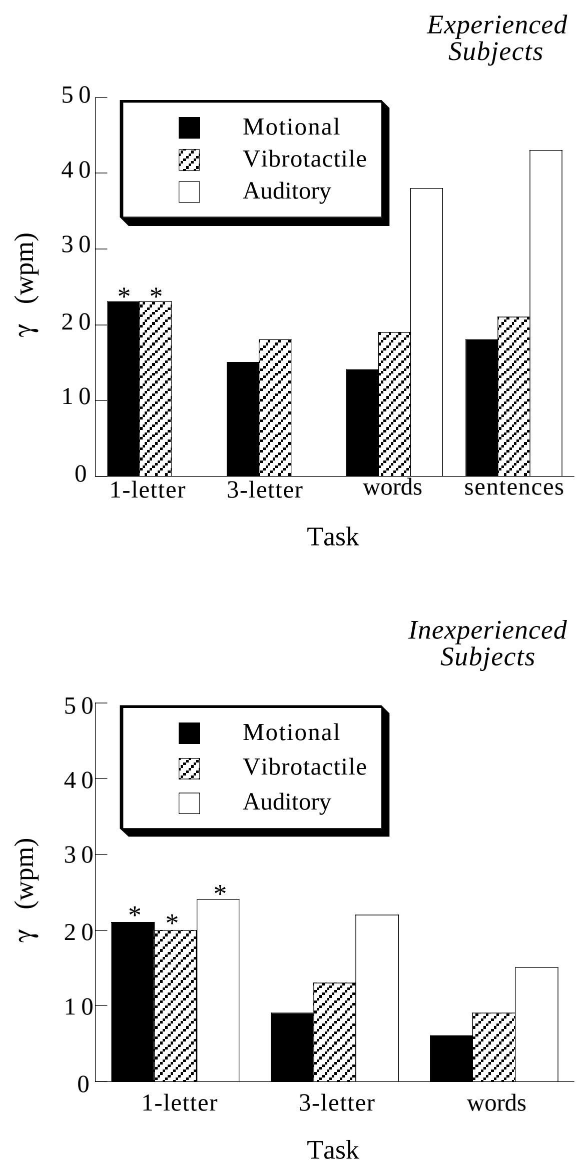

Figure A-9. Equivalent word rates γ (*wpm*) for each of the tasks and modes of stimulation. Upper panel presents results averaged across the two experienced subjects, and lower panel presents results averaged across the two inexperienced subjects.

The difference in the auditory and tactual rate of Morse code reception may be explained in terms of the unit signal length and the temporal properties of taction and audition. In general, the auditory system responds faster and more accurately to dynamic stimulation than the tactual system. For instance, Gescheider (1966) reported that the time difference necessary for resolving 2 successive events was 1.8 *msec* for equally loud binaural clicks and 10 *msec* for pulses applied to the fingertip. Our results can be compared quantitatively with those obtained by Lechelt (1957) on auditory and tactile numerousness perception using binaural clicks and 2-*msec* square-wave mechanical taps to the left middle finger with trains of 2 to 9 signals presented at rates of 3 to 8 *items/sec*. He found that whereas auditory counts were nearly perfect for all conditions tested, cutaneous counts tended to underestimate the actual number of signals. Cutaneous counts were about 90% of the actual number of signals at a presentation rate of 8 *items/sec*. Simplifying the Morse code as a series of dots (e.g., the code for "H" is *dit-dit-dit-dit*), a constant rate of 8 *items/sec* corresponds to a U value of 63 *msec*, or equivalently, 19 *wpm*. Despite the difference in signal duty cycles between Lechelt's study and ours, this is consistent with the equivalent word rate of 18 and 21 *wpm* with motional and vibrotactile stimulation, respectively, achieved by the experienced subjects.

The difference in performance between the two subject groups is evident in that whenever both subject groups performed the same tasks, experienced subjects attained higher values of γ than the inexperienced subjects. The inexperienced subjects were simply unable to perform some of the tasks, despite the fact that each subject received a total of 70-80 hours of training. The fact that the experienced subjects had more than 20 years of experience with the Morse code gave them several advantages over the inexperienced subjects. First, the experienced subjects were able to process finger motions at letter and word levels. The subjects reported that they could "hear" the code while feeling the motions on their fingers. This transfer of learning from the tactual sense to the auditory sense, a modality these subjects were highly trained on, allowed them to have more time to concentrate on the content of the message rather than focusing on the identification of single letters. Differences in the response strategy of the two subject groups for the common-word test material illustrate this point. The strategy of inexperienced subjects was to type out the responses letter by letter and then edit the string of letters into meaningful words. The experienced subjects, however, would either type out a whole word or skip a trial if they failed at word recognition. These subjects occasionally made spelling errors indicating again that they were focusing on words rather than letters. Second, the experienced subjects were well trained with "chunking" of letters into meaningful words or messages. They reported that during the reception of a word, they were constantly predicting the next letter based on letters already presented. This ability to hold letters in short term memory until they are incorporated into a meaningful unit is the result of years of practice. Finally, both of the experienced subjects used the straight key to send Morse code element by element before the more efficient iambic keyer became available. Their ability to send Morse code manually might have contributed to their ability to receive the code tactually.

To follow up the last point, a supplementary test was performed to determine the speed at which the experienced subjects could send Morse Code. They were tested with the straight key since its element-by-element mode corresponds directly to the mode used in our reception tests. The resulting speed for manually sending the Morse code of CUNY sentences was 23 *wpm* for each experienced subject.[5] This is consistent with the equivalent word rates obtained from sentence-reception tests with motional and vibrotactile stimulation (18 and 21 *wpm*, respectively; see the top panel of Fig. 9) for these experienced subjects.

The information transfer rates of several tactual communication methods can be compared. For natural methods of tactual communication, Reed, Durlach, & Delhorne (1992) estimated information transfer rates to range from 7.5 bits / sec for fingerspelling to 12-14 bits / sec for Tadoma and tactual sign language. Based on results obtained in the present study, the information transfer rate for receiving Morse code using conversational English material through motional and vibrotactile stimulation is roughly 2.7 bits / sec.[6] Foulke & Brodbeck (1968) reported that experienced Morse code operators were able to receive the code by electrocutaneous stimulation at a rate of 10 *wpm*, or roughly 1.3 *bits/sec* (according to note 5). These relatively low rates of tactual reception of Morse code are most likely limited not only by subjects' reception rate, but by major inefficiencies in the code; i.e., the bit-wise coding of information, the 3:1 dash-dot ratio, and the wasteful silences between dots and dashes. With the standard timing pattern for Morse code, the average duration across the 26 letters is roughly 8*U*. At a presentation rate of 20 *wpm* (i.e., *U* = 60 *msec*), the average duration for a letter is 480 *msec*.

Using his pneumatic reverse typewriter, Bliss (1961) reported that one experienced typist was able to receive letters and a few punctuation symbols at a rate of 4.5 *bits/sec* with a stimulus presentation rate of 1.32 symbols / sec and a stimulus uncertainty of 4.9 bits / presentation. Using the Optacon device (Linvill & Bliss, 1966) and English sentences as test material, Cholewiak et al. (1993) reported that their best subject was able to reach a word rate of 40 *wpm*, or 5.4 *bits/sec* (according to note 5). Using the display for the Vibratese language, Geldard (1957) reported that one subject was able to handle 38 wpm, or 5.1 *bits/sec* (according to note 5). These information-transfer rates are higher than those obtained here for Morse code. In making such a comparison, however, it should be noted that whereas our apparatus conveys Morse code through a 1-*bit* display, Bliss's device encodes letters and punctuation with each finger movement, the Optacon employs 108 stimulating pins (6×18, according to Fig. 47-1 in Cholewiak et al., 1993), and the Vibratese was coded using five vibrators with letters, numerals, and some short words as the basic elements.

5. In these tests, the subjects used a straight key oscillator (MFJ-557 from Tucker Electronics & Computers), the output of which was connected to a cassette recorder. Each subject was asked to send manually the Morse code of five CUNY sentence lists. They were instructed to (1) send as fast as they could assuming an excellent receiver, (2) not correct for any mistakes, and (3) take breaks only between sentences. The recording was then timed and scored by another ham radio operator. The sending speed for each sentence was computed as the number of words in the sentence divided by total time. The results were then averaged and multiplied by the overall percent-correct scores.
6. The information transfer rate was estimated as follows. The CUNY sentences contain 102 words per 12 sentences, thus averaging 8.5 word / sentence. According to Shannon (1951, Fig. 4), strings of that length have between 1.2 and 2.1 bits / letter. Using 2 bits / letter as the upper bound and 4 letters / word (from CUNY sentence statistics) as the average word length in the corpus, we estimated the information content to be 2 bits / letter × 4 letter / word, or 8 bits / word. Assuming that the experienced subjects can receive Morse codes of CUNY sentences reliably at 20 wpm (see top panel of Fig. A-9) through motional and vibrotactile stimulation, we conclude that the information transfer rate is 8 bits / word × 20 word / min, or equivalently, 2.7 bits / sec.

We are currently investigating the feasibility of communication through combined tactile and kinesthetic stimulation on multiple fingers using a novel multi-finger positional display. It is expected that by improving the encoding scheme as well as the display, we can achieve information rates comparable to those demonstrated by natural methods of tactual communication.

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APPENDIX

The International Morse Code

The International Morse Code is the original modulation method used in Amateur Radio. The two basic elements of Morse code are dot (sounded *dit*) and dash (sounded *dah*). It is usually received auditorily with fixed-frequency tones (usually between 500 *Hz* and 1500 *Hz*) indicating the presence and timing of *dits* and *dahs*. Unique combinations of *dits* and *dahs* specify the letters of the alphabet, numerals, punctuation marks, and procedure signals. For this study, we used letters only. A complete list of Morse Code for letters appears in Fig. A-10 with short and long bars indicating *dits* and *dahs*, respectively.

The length of a *dit*, *U*, is the basic unit of time in Morse Code. The duration of a *dah* is *3U*. Within a letter, the pause between adjacent elements is *U*. The space between letters is *3U*. The space between words or groups is *7U*. These relationships are illustrated in Fig. A-11.

The rate of Morse Code is expressed in terms of words per minute (*wpm*). The length of a "standard" word is defined as *50U*. The word "PARIS" is of this length and is used to accurately set transmission speed. The relationship between the length of a *dit*, *U*, and the rate of transmission, *R*, is:

$$U(\mathrm{second}) = 60/[R(wpm) \times 50] \qquad \text{(Eq. 4)}$$

or, equivalently,

$$U(\mathrm{millisecond}) = 1200/[R(wpm)] \ . \qquad \text{(Eq. 5)}$$

For instance, at 12 *wpm*, the duration of a *dit* is 100 msec and that of a *dah* is 300 *msec*.

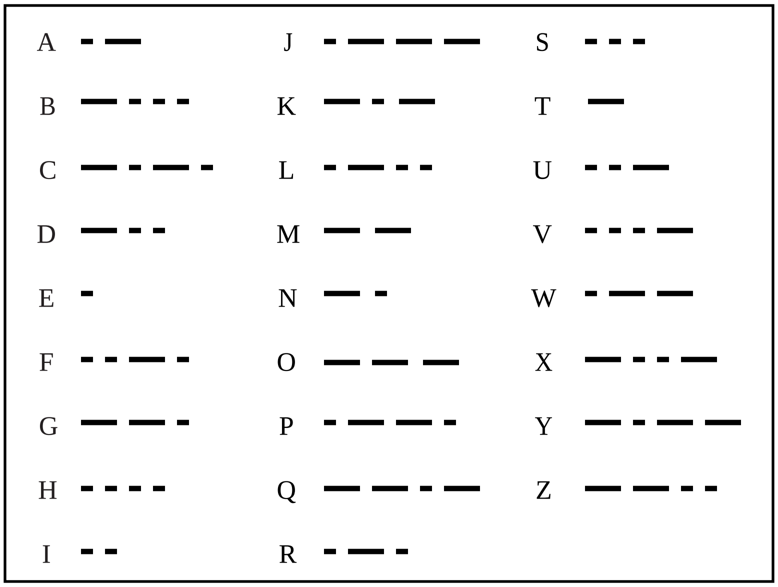

Figure A-10. Morse Code for Letters of the Alphabet

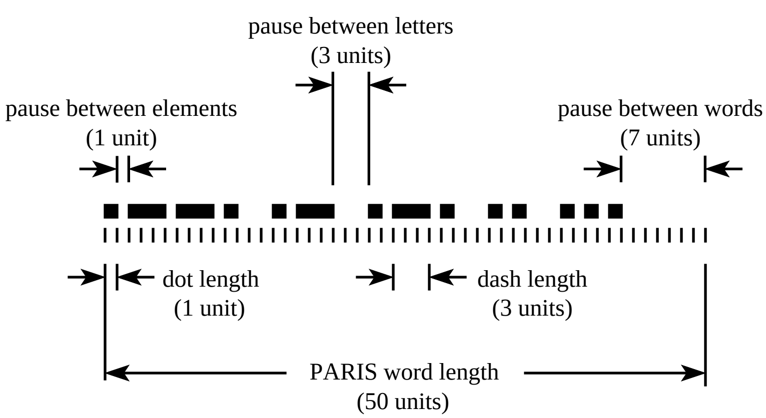

Figure A-11. Diagram of timing in International morse Code. (Adopted from *The ARRL Handbook for Radio Amateurs*.)