Temporal masking of multidimensional tactual stimuli

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Experiments were performed to examine the temporal masking properties of multidimensional tactual stimulation patterns delivered to the left index finger. The stimuli consisted of fixed-frequency sinusoidal motions in the kinesthetic (2 or 4 Hz), midfrequency (30 Hz), and cutaneous (300 Hz) frequency ranges. Seven stimuli composed of one, two, or three spectral components were constructed at each of two signal durations (125 or 250 ms). Subjects identified target signals under three different masking paradigms: forward masking, backward masking, and sandwiched masking (in which the target is presented between two maskers). Target identification was studied as a function of interstimulus interval (ISI) in the range 0 to 640 ms. For both signal durations, percent-correct scores increased with ISI for each of the three masking paradigms. Scores with forward and backward masking were similar and significantly higher than scores obtained with sandwiched masking. Analyses of error trials revealed that subjects showed a tendency to respond, more often than chance, with the *masker*, the *composite* of the masker and target, or the combination of the target and a *component* of the masker. The current results are compared to those obtained in previous studies of tactual recognition masking with brief cutaneous spatial patterns. The results are also discussed in terms of estimates of information transfer (IT) and IT rate, are compared to previous studies with multidimensional tactual signals, and are related to research on the development of tactual aids for the deaf.
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I. INTRODUCTION

A goal of recent research on the development of tactual aids for the deaf and deaf–blind is to demonstrate communication rates comparable to those observed for natural methods of tactual communication (e.g., see Reed, Durlach, and Delhorne, 1992). One approach to improving the information-transfer rate capacity of artificial tactual devices is through modifications designed to increase the perceptual richness or dimensionality of the output display (e.g., see Reed *et al.*, 1985; Leotta *et al.*, 1988; Eberhardt *et al.*, 1994; Tan and Rabinowitz, 1996; Rinker, Craig, and Bernstein, 1998; Tan *et al.*, 1999). In addition to providing stimulation of the cutaneous component of the tactual sensory system, similar to most older tactile devices (e.g., see reviews by Kirman, 1973; Reed, Durlach, and Braida, 1982; Reed *et al.*, 1989; Bernstein, 1992), the more recent displays have also incorporated stimulation of the kinesthetic component of the tactual system.[1] The design of these displays is motivated in part by the display characteristics of natural methods of tactual communication employed by deaf–blind individuals (Reed *et al.*, 1992), by basic principles governing information transfer (Garner, 1962), and by physiological and psychophysical studies of the separate channels of the tactual system and their interactions (Bolanowski *et al.*, 1988; Johnson, Yoshioka, and Vega-Bermudez, 2000). The current study is concerned with further investigation of the perception of multidimensional tactual signals presented through a multifinger tactual display designed to provide stimulation of the tactual sensory system along a continuum from kinesthetic movements to cutaneous vibrations (Tan, 1996; Tan and Rabinowitz, 1996).

Previous research (Tan, 1996; Tan *et al.*, 1997; Tan *et al.*, 1999) investigated information transfer (IT) for sets of multidimensional stimuli created using signal components selected from each of three perceptually distinct regions: slow motion (from dc to roughly 6 Hz), fluttering motion (in the region of roughly 10–70 Hz), and smooth vibration (above roughly 150 Hz). One or two (highly discriminable) frequencies were selected from each of these three spectral regions. Stimuli were constructed using single-frequency waveforms, double-frequency waveforms (composed of one frequency component from each of two different spectral regions), and triple-frequency waveforms (composed of one frequency component from each of three different spectral regions). Three stimulus sets were constructed at three signal durations of 125, 250, and 500 ms. (At some values of frequency and duration, amplitude and onset direction of movement were also used as distinguishing characteristics of the stimulus waveforms.) The total number of distinct waveforms was 30 for the 250-ms and 500-ms stimulus sets and 19 for the 125-ms set. In addition, each waveform could be

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presented at one of four possible locations (thumb, index finger, middle finger, or all three digits simultaneously), leading to stimulus uncertainty of 6.25 bits (at 125 ms) or 6.91 bits (at the two longer durations).

Estimates of static IT were derived from percent-correct scores (using an empirically derived formulation described by Tan *et al.*, 1999) obtained under a one-interval, forced-choice identification procedure with 120 alternatives (for the two 250- and 500-ms stimulus sets) or 76 alternatives (for the 125-ms stimulus set). Static IT, averaged across three subjects, was estimated to be 5.6 to 6.5 bits for the three stimulus sets.

Estimates of IT *rate* were obtained using a highly simplified procedure (referred to as an AXB paradigm) that required subjects to identify a signal X that was preceded by signal A and followed by signal B. These experiments employed the stimulus sets described above with the exception that waveforms were presented at one of three (rather than four) possible locations. Signals and maskers were always of equal duration, did not overlap in time, and were separated by the same value of inter-stimulus interval (ISI), that is, the time between the offset of one stimulus and the onset of the next stimulus within a given trial. Different presentation rates were achieved at each signal duration by varying the value of ISI, also expressed in terms of stimulus-onset asynchrony (SOA) which is defined as the time between the onsets of two adjacent stimuli in a given trial. IT rate in bits/s was calculated as the product of IT in bits/item (estimated from percent-correct scores) and the presentation rate in items/s (the reciprocal of the SOA). Maximum values of IT rate achieved in these previous experiments were roughly 12 bits/s and occurred at SOA values ranging from 350–500 ms (i.e., 2–3 items/s and consistent with previous observations of Garner, 1962, pp. 90–93). These estimated IT rates fall within the range of estimates of maximal IT rates for natural methods of tactual communication (see Reed and Durlach, 1998) and are among the highest observed to date with an artificial tactual display. It should be noted, however, that these estimates are based on the strong assumption that the identification performance observed in the AXB paradigm could (with sufficient training) be maintained for identifying streams of signals (such as those that would be encountered in using signals such as these to encode the acoustic speech signal). These estimates can reasonably be assumed to represent an upper bound on IT rate for continuous signals. The relation between these upper-bound estimates of IT rate and the actual IT rate that can be achieved for continuous streams of signals, however, requires further experimental study.

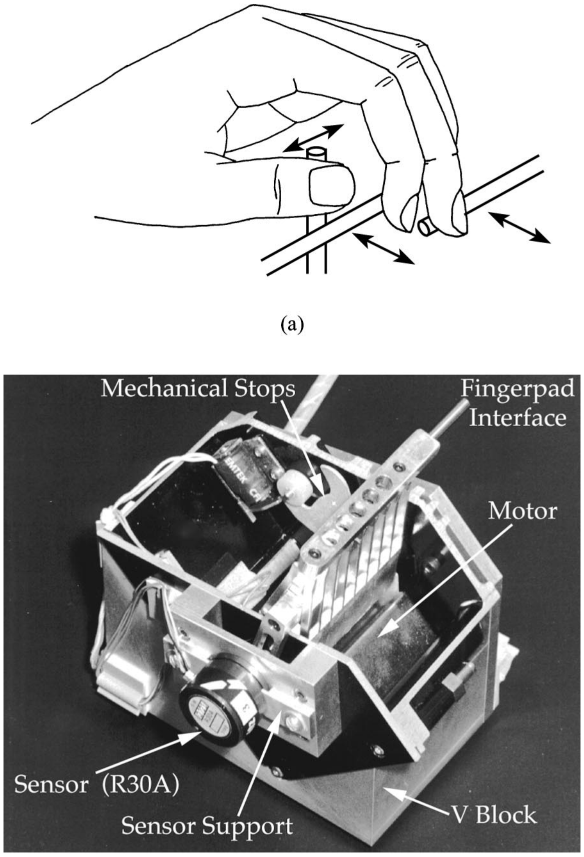
The current research is concerned with further investigation of the interactions between adjacent signals in the identification of multidimensional tactual stimuli presented in sequences. In the AXB paradigm used by Tan *et al.* (1999) to derive estimates of IT rate, identification of the target signal X was based on the combined effects of a forward masker (A) and a backward masker (B) at stimulation sites that were selected randomly (from a set of three possible sites) for each target and masker. The purpose of the current study was to investigate the separate effects of forward and backward masking (as well as their combined effects using the AXB paradigm employed previously) on the identification of tactual stimuli at a single site (which would presumably maximize temporal masking effects). The stimuli employed in these studies were a small subset of the multidimensional stimuli developed by Tan (1996) and were presented at only one site (the left index finger). Two stimulus sets were constructed at each of two signal durations (125 and 250 ms). Each stimulus set was made up of seven waveforms: three single-frequency waveforms (one from each of the three distinct spectral regions described above), three double-frequency waveforms (resulting from all possible combinations of the three single waveforms), and one triple-frequency waveform (composed of the three single-frequency waveforms). Under each of the three masking paradigms, target identification was studied as a function of interstimulus interval for seven values in the range 0–640 ms. Targets and maskers were always selected at random from the same stimulus set. The results are summarized by functions describing overall performance in percent-correct performance and IT as a function of SOA. In addition, error trials are analyzed to gain insight into the underlying structure of the errors. The results of the current study are compared both to our own previous studies of IT and IT rate for multidimensional tactual stimuli (Tan *et al.*, 1999) and to previous studies of tactual recognition masking using cutaneous spatial-pattern displays (e.g., Craig, 1983, 1995; Evans and Craig, 1986; Evans, 1987).

II. METHODS

A. Apparatus

The experimental apparatus (the Tactuator) consists of three independent, point-contact, one-degree-of-freedom actuators interfaced individually with the fingerpads of the thumb, the index finger, and the middle finger [Fig. 1(a)]. The motion trajectory for the thumb is perpendicular to that of the index and middle fingers, thereby maintaining an approximately natural hand configuration with the wrist resting in its neutral position. The range of motion provided by the display for each digit is about 26 mm. All motions begin and end with each of the three digits at the middle of its respective range of motion. Each digit can thus be moved either outward (extension) or inward (flexion).

Each actuator utilizes a disk-drive head-positioning motor augmented with angular position feedback from a precision rotary variable differential transformer which has a response bandwidth (−3 dB) of 1 kHz and effectively infinite resolution due to its electromagnetic coupling [Fig. 1(b)]. Real-time positional control is provided by a digital PID controller implemented on a floating-point DSP system with 16-bit analog-to-digital and digital-to-analog converters. The overall system performance is well suited for this study for several reasons. First, each movement channel has a *continuous* frequency response from dc to 300 Hz (the disk-drive motor ceases to move beyond about 400 Hz). Therefore, the Tactuator can deliver stimulation in the kinesthetic (i.e., low-frequency gross motion) and cutaneous (i.e., high-frequency vibration) ranges as well as in the midfrequency range. Stimuli with any desired spectral components can be realized



(a)

(b)

FIG. 1. The Tactuator. (a) Schematic drawing illustrating finger placement on the Tactuator and the motion trajectories of the thumb, index, and middle fingers. (b) Photograph of one of the three associated motor assemblies with its components labeled. The subject rests the fingerpad on the rod labeled ‘‘finger interface’’ in (b).

within the frequency range of dc to 300 Hz. Second, across the frequency range of dc to 300 Hz, an amplitude of at least 47 dB SL *per frequency* can be achieved. This stimulus range is well matched to the human's sensory range in that stimulation levels exceeding 50–55-dB SL tend to induce discomfort and fatigue (Verrillo and Gescheider, 1992). Third, measurements with single- and multiple-frequency inputs at various amplitude levels indicate that each channel is highly linear, harmonic distortion is low, and interchannel crosstalk is small. This allows high-fidelity delivery of waveforms of arbitrary frequency content and stimulation level (e.g., a 30-μm high-frequency vibration superimposed on a 26-mm low-frequency motion) simultaneously to all fingers. Fourth, ‘‘loading’’ a movement channel (i.e., resting a finger lightly on the actuator's moving bar) does not significantly alter the intended stimuli. Selected measurements indicate that loading reduces the magnitude of stimulation by an average of 1.5 dB at 2 Hz, 2.7 dB at 20 Hz, and 0.1 dB at 200 Hz. This does not pose a significant problem for the experiments reported here because the stimuli are generally strong (i.e., at least 40 dB SL) and only one amplitude value is used per spectral component of a fixed frequency.

A more detailed description of the Tactuator and its performance characteristics can be found in Tan and Rabinowitz (1996).

B. Stimuli

In our earlier study (Tan *et al.*, 1999), the following stimulus attributes associated with fixed-frequency sinusoidal movement profiles were found to be effective in creating a multiattribute stimulus set with the Tactuator: frequency, amplitude, duration, site of stimulation, and signal onset direction (for gross motions only). For example, a typical stimulus employed in that study was a 125-ms 4-Hz motion at 35 dB SL delivered to the middle finger with an onset direction of extension. Signals of different frequencies were also combined to create double-frequency and triple-frequency stimuli.

Our current study employed two stimulus sets (each of which was applied only to the left index finger), referred to as the 250-ms and 125-ms stimulus sets, that are subsets of the ones used in Tan *et al.* (1999).[2] The stimulus sets were designed so that (1) subjects could learn to identify all of the stimulus alternatives easily, and (2) errors in a recognition-masking task could be attributed to masking effects rather than to the difficulties of recognizing complex stimuli. The 250-ms stimulus set contained a 2-Hz low-frequency component at 44 dB SL, a 30-Hz midfrequency component at 40 dB SL, a 300-Hz high-frequency component at 47 dB SL, and their combinations (Table I, third column). The seven stimuli in the 125-ms stimulus set were identical to those in the 250-ms set except that the 2-Hz component was replaced by 4 Hz, so that the movement started and ended at the same (resting) position (Table I, fourth column). All sensation levels were calculated from the absolute detection thresholds measured previously with the Tactuator (35, 34, 23.5, and −18 dB *re*: 1-μm peak at 2, 4, 30, and 300 Hz,

TABLE I. Signals in the 250- and 125-ms stimulus sets.

Category	Symbol[a]	Waveform at 250 ms	Waveform at 125 ms
Single-frequency	F_L	(2,44)	(4,44)
	F_M	(30,40)	(30,40)
	F_H	(300,47)	(300,47)
Double-frequency	F_L+F_M	(2,44)+(30,40)	(4,44)+(30,40)
	F_L+F_H	(2,44)+(300,47)	(4,44)+(300,47)
	F_M+F_H	(30,40)+(300,47)	(30,40)+(300,47)
Triple-frequency	$F_L+F_M+F_H$	(2,44)+(30,40)+(300,47)	(4,44)+(30,40)+(300,47)

[a] F_L, F_M, and F_H refer to low, medium, and high-frequency components, respectively. The units given within each pair of parentheses are the frequency in hertz and the amplitude in decibels (SL), respectively. The ‘‘+’’ sign indicates that the waveforms are added to form a new signal.

respectively—see Tan and Rabinowitz, 1996). The actual peak displacements at the fingertip for the four single-frequency sinusoidal signals were 8.9, 7.9, 1.5, and 0.028 mm at 2, 4, 30, and 300 Hz, respectively. All signals in both stimulus sets started in the finger-extension direction, and were delivered to the index fingertip of the left hand.

These signals could be easily discriminated and identified in isolation. The 2-Hz or 4-Hz low-frequency signal was perceived as a movement that extended the index finger and then brought it back to its resting position. The 30-Hz mid-frequency signal gave rise to a mixed flutter/rough sensation. The 300-Hz high-frequency signal felt like a smooth and penetrating vibration. When two or three of the single-frequency components were combined, the perceptual qualities associated with each component could still be discerned. For example, the percept of a 2-Hz and 30-Hz combination signal was a ''wobbly/rough'' extension and flexion of the index finger. The fact that the individual signal components retained their perceptual distinctiveness is consistent with the idea that they evoke separate mechanoreceptor channels in the skin surface (Bolanowski *et al.*, 1988; Johnson *et al.*, 2000).

C. Responses

In consideration of stimulus–response compatibility, response codes based on graphic icons, similar to those used by Tan *et al.* (1999), were employed in this study. The icon layout was placed on a digitizing tablet. Subjects used a stylus to press the appropriate icon as a response, followed by an ''ENTER'' icon. A ''DEL'' icon was available for deleting a response entered by mistake. The subject then reselected the intended response, followed by ''ENTER.'' The same response setup was used for both the 250-ms and the 125-ms stimulus sets.

D. Subjects

Three subjects participated in the experiments. S1 had participated as a subject in pilot studies that involved training on the identification of seven stimuli (similar to those used in this study) at a duration of 500 ms. S2 had previous experience in a different type of tactual experiment. S3 had participated in a previous study on the information transmission capabilities of the Tactuator (Tan *et al.*, 1999) and other tactual perception studies. S2 and S3 were paid for their participation in this study. None of the subjects reported any known tactual impairments of their hands.

E. Masking paradigms

Three masking paradigms were employed in this study: forward, backward, and ''sandwiched'' masking. In the forward-masking paradigm, the forward masker (M_F) is presented before the target signal (T). In the backward-masking paradigm, the backward masker ($\mathrm{M_B}$) is presented after the target signal (T). In the ''sandwiched''-masking paradigm, the target (T) is sandwiched between a forward masker (M_F) and a backward masker (M_B). Interstimulus interval (ISI) is defined as the time between the offset of one stimulus (either a target or a masker) and the onset of the next stimulus in a given trial. Stimulus-onset asynchrony (SOA) is defined as the time between the onset of the target and the onset of the masker, with positive values of SOA indicating that the target preceded the masker (backward masking) and negative values of SOA indicating that the masker preceded the target (forward masking). In this study, the duration of the target and masker(s) was always kept the same. The maskers were selected from the same stimulus set as the stimuli. On a particular trial, each target and masker signal was selected from the seven stimuli in the 250-ms (or 125-ms) stimulus set with equal *a priori* probabilities using randomization with replacement.

F. Procedures

Prior to the masking experiment, subjects were trained to identify the seven target signals employed at each of the two durations. Training was conducted using a one-interval, seven-alternative, forced-choice procedure with trial-by-trial correct-answer feedback. The goal of this training was to familiarize the subjects with the signals and to produce near-perfect identification of signals presented in isolation. Different amounts of training were required by each of the three subjects at each duration, dependent primarily on their previous experience with the signals. Both S1 and S3 had previous experience with stimuli similar to those used in the current study, and thus required less training than S2. S1 received 10 runs (140 trials per run) with the 250-ms signals and 9 runs with the 125-ms signals. S2 received 38 runs at 250 ms and 3 runs at 125 ms. S3 received 2 runs at 250 ms and 1 run at 125 ms. Training was terminated when the subjects demonstrated consistent identification scores in the range 95%–100% correct.

The independent variables of this study were signal duration (250 or 125 ms), masking paradigm (forward, backward, or sandwiched), and ISI (interstimulus intervals: 0, 20, 40, 80, 160, 320, or 640 ms). For each subject, a total of six (6) 100-trial runs was conducted per duration–paradigm–ISI combination.[3] Each subject was tested with the 250-ms stimulus set first. For each stimulus set, the order of the experimental paradigms was always forward, backward, and sandwiched masking. For each duration–paradigm combination, the order of the ISI values was randomized for each subject.

The subject was instructed as to the temporal location of the target signal within the stimulus sequence under each of the three masking paradigms, and was told to identity only the target and to ignore the masker(s). During the experiments, the Tactuator was placed to the left of the subject's torso. It was covered by a padded wooden box that served as an armrest for the subject's left forearm. The top of the box had an opening that allowed the subject to place the left index finger on the ''fingerpad interface'' rod as shown in Fig. 1(b). Earplugs and earphones with pink noise were used to eliminate possible auditory cues. (The Tactuator produces little audible noise except in the neighborhood of 300 Hz.) Correct-answer feedback was not provided during the main experiments for two reasons. First, all subjects were well trained with the signals in the two stimulus sets. Second, requiring the subjects to attend to correct-answer feedback

TABLE II. Analysis of masker (A), composite (B), and component (C) responses for the 125-ms stimulus set with backward masking. See the text for details.

(A)	SOA (ms)	Total trials	Skipped trials	Correct trials	Error trials	$M \neq T$ trials	$R = M$ trials	$R = M$ given $M \neq T$	$R = M$ given all errors
	125	1800	52	1248	500	476	189	39.71%	37.80%

(B)	SOA (ms)	Total trials	Error trials	T/M Nonoverlapping trials	$R = T + M$ trials	$R = T + M$ given nonoverlapping T/M	$R = T + M$ given all errors
	125	1800	500	100	29	29.00%	5.80%

(C)	SOA (ms)	Error trials	$F_L \in M$ trials	$R = T + F_L$ trials	$F_M \in M$ trials	$R = T + F_M$ trials	$F_H \in M$ trials	$R = T + F_H$ trials
	125	500	35	10	49	22	45	12
	145	440	29	9	46	28	45	15
	165	368	42	11	32	18	29	13
	205	321	21	6	28	18	23	10
	285	230	8	1	15	12	21	11
	445	121	6	1	4	4	7	6
	765	87	7	0	2	2	7	5
Total			148	38	176	104	177	72
Percentage				25.7%		59.1%		40.7%

tended to break the “rhythm” of the experiment. Subjects were instructed to use their right hand to select one of the seven stimulus alternatives on the digitizing tablet after each trial and then press “ENTER” to initiate the next trial. Occasionally, however, subjects hit “ENTER” before selecting a response, thus leading to “skipped trials.” The number of skipped trials accounted for roughly 2.5% of the total trials across all subjects and conditions. These skipped trials were not included in the data processing.

G. Data analyses

1. Overall percent-correct score

The overall performance level in percent correct was computed for each subject under each experimental condition (i.e., each combination of duration, masking paradigm and SOA). The percent-correct score was calculated separately for each individual run based only on the trials to which the subject had entered a legitimate response (i.e., skipped trials were ignored). The percent-correct scores were averaged across the individual runs for each subject at each experimental condition. Scores for individual subjects were examined as a function of SOA for each of the three masking paradigms at each of the two durations.

Conditional analyses of incorrect responses were carried out to gain further insight into the structure of the errors, using data pooled across the three subjects for each experimental condition (i.e., each masking paradigm and each SOA). The data from the sandwiched-masking paradigm were analyzed twice: first by examining the effect of the forward masker on the identification of the target (referred to as sandwiched masking M_F) and second by examining the effect of the backward masker on the identification of the target (referred to as sandwiched masking M_B). Each of three separate analyses of the error responses (i.e., masker-response analysis, composite-response analysis, and component-response analysis) is described below.

2. Masker-response analysis

A “masker response” is defined as an error consisting of the use of the label associated with the masker as the response. Only those trials on which the masker and target consisted of different signals were included in this analysis. Of the 49 possible masker–target combinations (7 maskers×7 targets), the seven combinations where the masker and target consisted of the same signals were eliminated from further consideration in this analysis, thus leaving 42 combinations of nonidentical target and masker pairs for analysis. The percentage of masker responses, “$R = M$ given $M \neq T(\%)$” (where R denotes response, and M refers to either the forward masker M_F or the backward masker M_B), was calculated as the ratio of the number of trials where the masker label was used as the response, over the total number of error trials where the masker and target were different.

An example of the computation of the percentage of masker responses is provided in Table IIA for one experimental condition (backward masking, 125-ms duration, 125-ms SOA). Each subject contributed 600 trials to this condition, for a total of 1800 pooled trials (the entry in column 2). These 1800 trials were sorted into three categories: skipped trials (the number of trials on which no response was provided by the subject, shown in column 3), correct trials (the number of trials on which the subject identified the target correctly, column 4), and error trials (the number of trials on which the subject entered an incorrect response, column 5). The error trials were further sorted into two categories: those where the masker and target consisted of the same stimulus ($M = T$ trials, not shown) and those where the masker and target were nonidentical stimuli ($M \neq T$ trials, shown in column 6). The $M = T$ trials were discarded in this analysis, and only those error trials in which $M \neq T$ were used to examine the use of the masker as response. The number of $M \neq T$ trials on which the subjects erroneously responded with the label of the masker is shown in column 7

($R=M$ trials) of Table IIA. The percentage of $R=M$ responses relative to the number of $M\neq T$ trials is provided in column 8 ($R=M$ given $M\neq T$). The percentage of $R=M$ responses relative to the total number of error trials is provided in the final column ($R=M$ given all errors). Data were processed in an analogous manner for all values of SOA for forward and backward masking at both signal durations. In addition, data from the sandwiched-masking paradigm were processed twice in this manner: once considering only the forward masker (designated M_{F}) and once considering only the backward masker (M_{B}).

3. Composite-response analysis

The percentage of composite responses was calculated to examine the extent of temporal integration of the target and masker. A composite response was possible only in those cases where the spectral components of the masker and target were both nonoverlapping and combined to form another member of the stimulus set. Only 12 of the 49 possible target and masker combinations met these specifications (i.e., did not have overlapping spectral components and combined to form another member of the stimulus set). Therefore, the error trials corresponding to these 12 combinations were analyzed for composite responses. The percentage of composite response, ‘‘$R=T+M\,(\%)$’’, was calculated as the ratio of the number of trials where the response was the same as the composite of the target and masker, over the total number of error trials where the target and masker did not share any spectral components.

An example of the computation of the percentage of composite responses is provided in Table IIB, again for one experimental condition (backward masking, 125-ms duration, 125-ms SOA). The total number of pooled trials (column 2) and the error trials (column 3) were calculated in the same way as those in Table IIA. For this analysis, the error trials were further sorted into two categories: those where the masker and target shared one or more components (not shown) and those where the masker and target did not share any spectral components (T/M nonoverlapping trials, column 4). The number of T/M nonoverlapping trials on which the subjects erroneously responded with the composite of the masker and the target is shown in column 5 ($R=T+M$ trials) of Table IIB. The percentage of $R=T+M$ responses relative to the number of T/M nonoverlapping trials is provided in column 6 ($R=T+M$ given nonoverlapping T/M). The percentage of $R=T+M$ responses relative to the total number of error trials is provided in column 7 ($R=T+M$ given all errors). Data were processed in an analogous manner for all values of SOA for forward and backward masking at both signal durations. In addition, data from the sandwiched-masking paradigm were processed twice in this manner: once considering only the forward masker (designated M_{F}) and once considering only the backward masker (M_{B}).

4. Component-response analysis

A component response was defined as a case in which a frequency component that was present in the masker, but not in the target, was contained in an incorrect response. The analysis was thus restricted to those error trials where the target and masker did not share any common frequency components. The masking effects of the low-, mid-, and high-frequency components were analyzed separately in terms of the percentages of F_L, F_M, or F_H component responses, using the relevant subset of error trials.

An example of the computation of the percentage of component responses is provided in Table IIC for one experimental condition (backward masking, 125-ms duration). For the analysis on low-frequency component response, the error trials shown in column 2 were further sorted into two categories: those where the masker contained a low-frequency component ($F_L\in M$ trials, column 3) and those where the masker did not contain such a component (not shown). Of those error trials where the masker contained a low-frequency component, the number of trials on which the subjects erroneously responded with the composite of the target and a low-frequency component is shown in column 4 ($R=T+F_L$ trials). The number of $F_L\in M$ and $R=T+F_L$ trials were further pooled across all SOA values (shown in the ‘‘Total’’ row towards the end of Table IIC). The percentage of $R=T+F_L$ responses relative to the number of $F_L\in M$ trials is provided on the last row in column 4. Data were processed in an analogous manner for midfrequency and highfrequency component responses as shown in Table IIC. The same data processing procedure was applied to forward and backward masking at both signal durations. In addition, data from the sandwiched masking paradigm were processed twice in this manner: once considering only the forward masker (designated M_{F}) and once considering only the backward masker (M_{B}).

5. Information-transmission analysis

Information transfer (IT) and information-transfer rate (IT rate) were estimated from percent-correct scores for each subject. IT was calculated as $IS\times(1-2e)$, where IS is the information in the stimulus, and e is the error rate. This formula has been used to obtain a lower-bound estimate of IT when the total number of trials is small (see Tan, 1996). When all stimulus alternatives are equally likely (as was the case in the current study), IS is simply $\log_2 k$, where $k=7$ is the number of stimulus alternatives (that is, $IS=2.81$ bits for all experiments considered here). Error rate e was calculated as $(1-pc)$, where pc stands for percent-correct scores in percentages. For cases in which pc was below 50%, IT was set to 0.

The estimated values of IT at each combination of stimulus duration and SOA were used to calculate estimates of IT rate in bits/s. Specifically, IT rate was calculated as the product of estimated IT in bits/item and presentation rate in items/s. The presentation rate is simply the reciprocal of the SOA (i.e., ISI plus stimulus duration in seconds).

III. RESULTS

A. Overall percent-correct score

The overall performance levels of each subject under the three masking paradigms are shown in Fig. 2 for the 250-ms

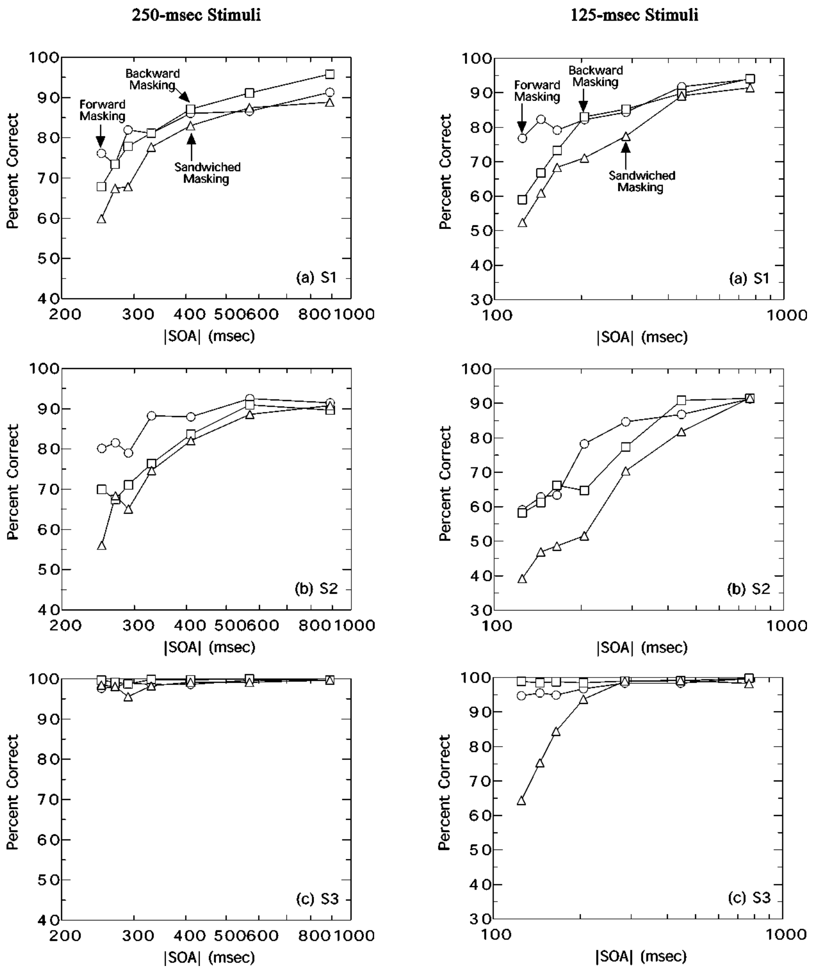


FIG. 2. Percentage-correct scores for the 250-s (left column) and 125-ms (right column) stimulus sets for subjects S1, S2, and S3 (top, middle, and bottom rows, respectively). Data from forward, backward, and sandwiched masking paradigms are shown by open circles, open squares, and open triangles, respectively. Data are plotted against the absolute value of SOA (negative for forward masking and positive for backward masking).

stimulus set (left column) and the 125-ms stimulus set (right column). At 250-ms, S3 had essentially errorless performance at all values of SOA under all three types of masking. The performance of S1 and S2, on the other hand, began to decrease steadily with a decrease in SOA under all three types of masking. For both these subjects, a tendency was observed for worst performance under sandwiched masking and for the highest performance under forward masking, particularly at the shortest values of SOA. At 125 ms, the performance of S3 was again quite high and began to deteriorate only under sandwiched masking (at the three shortest values of SOA). S1 and S2 demonstrated deteriorating performance with SOA under all three masking paradigms. For S1, performance was worst under sandwiched masking and best for forward masking at the three shortest values of SOA. For S2, performance was worst under sandwiched masking but similar for forward and backward masking conditions at the shortest values of SOA. Our observation that forward masking produced similar or better results than backward masking at the shortest SOA values is inconsistent with the general consensus in the literature that, under similar conditions, there is more interference in backward masking than in forward masking (see, for example, Craig and Evans, 1995). A trend toward lower scores for backward compared to forward masking was observed at shorter values of ISI for S1 (at both stimulus durations) and for S2 (at 250 ms only). The finding that performance level was lower with the sandwiched-masking paradigm was to be expected since signal identification in the sandwiched-masking paradigm was affected by both the forward and backward maskers.

From the individual-subject data in Fig. 2, it is clear that S3 performed near 100% correct at all SOA values (except for the sandwiched masking at 125 ms), whereas S1 and S2 made more errors at smaller SOA values. This intersubject difference may be attributed to the fact that S3 had participated in an earlier study requiring the identification of similar signals from a much larger set of stimulus alternatives.

B. Masker response

Masker responses are the percentages of error trials where the masker and target were different, and subjects responded with the masker (see the column "$R=M$ given $M \neq T$" in Table IIA). The chance performance level was 12.2%. This was calculated as the multiplication of 42/49 (probability of a target and masker combination where $T \neq M$) and 1/7 (probability of choosing the masker as the response given the target and masker combination, assuming that the subject's response was independent of the target or masker). The percentages of masker responses were well above chance level for both the 250- and 125-ms stimulus sets. For the 250-ms stimuli, the level of masker response was in the range 15%–32%. Percentage of masker responses was higher for the 125-ms stimuli, falling in the range 21%–

TABLE III. Percentages of component responses and the corresponding number of trials analyzed (in parentheses).

Components	Forward		Backward		Sandwiched (M_F)		Sandwiched (M_B)	
	250 ms	125 ms	250 ms	125 ms	250 ms	125 ms	250 ms	125 ms
F_L	11.1% (144)	26.9% (171)	11.5% (148)	25.7% (148)	13.2% (204)	19.5% (251)	13.6% (169)	25.7% (261)
F_M	60.0% (30)	75.5% (94)	43.1% (72)	59.1% (176)	39.6% (91)	45.9% (281)	43.4% (106)	44.0% (273)
F_H	64.7% (133)	52.4% (170)	51.3% (150)	40.7% (177)	62.2% (164)	28.9% (374)	52.0% (179)	31.3% (335)

45%. The result of a three-way ANOVA (on the factors of stimulus duration, masking paradigm, and ISI[4]) performed on the percentages confirmed a significant main effect of stimulus duration $[F(1,18)=58.26,\ p<0.0001]$, and ISI $[F(6,18)=5.94,\ p=0.0014]$. The latter was consistent with the fact that subjects responded with the masker more often for small ISI values.

C. Composite response

Composite responses are the percentages of error trials (see the column "$R=T+M$ given nonoverlapping T/M" in Table IIB) where subjects responded with the composite of the target and masker. The chance performance level was 3.5%. This was calculated as the multiplication of 12/49 (probability of a valid target and masker combination) and 1/7 (probability of choosing the composite of the target and masker as the response given the target and masker combination, assuming that the subject's response was independent of the target or masker). The percentages of composite responses were well above chance level for both the 250- and 125-ms stimulus sets. The level of composite response was in the range 14%–48% for the 250 ms stimuli, and 25%–54% for the 125-ms stimuli. It was observed that subjects responded with the composite of the target and masker significantly more often with the 125-ms stimuli than with the 250-ms stimuli. The result of a three-way ANOVA (on the factors of stimulus duration, masking paradigm, and ISI) performed on the percentages confirmed a significant main effect only for stimulus duration $[F(1,18)=14.64,\ p=0.0012]$.

D. Component response

Recall that component-response analysis examines the extent to which a particular spectral component in the masker was combined with the target response to form an incorrect response. Table III contains the percentages of component responses for the three single-frequency components and the four masking categories at 250 and 125 ms. Note that the entries in the last two rows of Table IIC are entered into column 5 of Table III (backward, 125 ms). The chance performance level for the F_L, F_M, or F_H component was 1.5%. For example, the chance level for F_L component response was the multiplication of 5/49 (probability of the joint event that the target and masker did not share any spectral components and the masker contained an F_L component) and 1/7 (probability of choosing the composite of the target and F_L as the response, assuming that the subject's response was independent of the target or masker). From Table III, it is clear that the percentage of component responses under each category was in the range 11%–76% and was well above the chance level of 1.5%, indicating that subjects indeed responded erroneously by choosing a response based on the combination of the target and a component of the masker.

A three-way ANOVA was conducted on the results presented in Table III for the three main factors of masking paradigm, stimulus duration, and frequency of the masking component. The results indicated that the rate of usage of the component response was dependent on masking paradigm $[F(3,6)=21.26,\ p<0.001]$ and on the frequency of the masking component $[F(2,6)=228.76,\ p<0.0001]$, but not on stimulus duration $[F(1,6)=0.36,\ p<0.57]$. A higher rate of component response was observed under forward masking (11%–76%, average 48.4%) than under the other three paradigms (12%–62%, average 36.2%). Component responses were least likely to occur with F_L (11%–27%, average 18.4%) compared to F_M (40%–76%, average 51.3%) and F_H (29%–65%, average 47.9%).

E. Information transmission

Estimated information transfer (IT) is plotted as a function of the absolute value of SOA ($|\mathrm{SOA}|$) in Fig. 3 for each of the three subjects. Because the estimated IT values are derived from a multiplicative transformation of the percent-correct scores, the trends observed previously for percent-correct scores also apply to the IT measure. The IT values are limited by the stimulus uncertainty of 2.81 bits in these experiments. Across conditions for the 250-ms stimuli, estimated values of IT ranged from roughly 0.5 to 2.6 bits for S1, 0.25 to 2.25 bits for S2, and 2.6 to 2.75 bits for S3. Across conditions for the 125-ms stimuli, IT ranged from roughly 0.13 to 2.5 bits for S1, 0 to 2.25 bits for S2, and 0.75 to 2.75 bits for S3.

In Fig. 4, estimated IT rate in bits/s is plotted as a function of the actual information presentation rate. Data for each subject are plotted separately in each of the three panels of the figure. The information-presentation rate was computed as stimulus uncertainty (2.81 bits) divided by $|\mathrm{SOA}|$. In general, IT rate was close to the information-presentation rate (i.e., the maximum achievable IT rate, shown by the dashed lines in Fig. 4) when information presentation rate was low (i.e., when $|\mathrm{SOA}|$ was large). IT rate deviates from the dashed lines as information-presentation rate increases. The

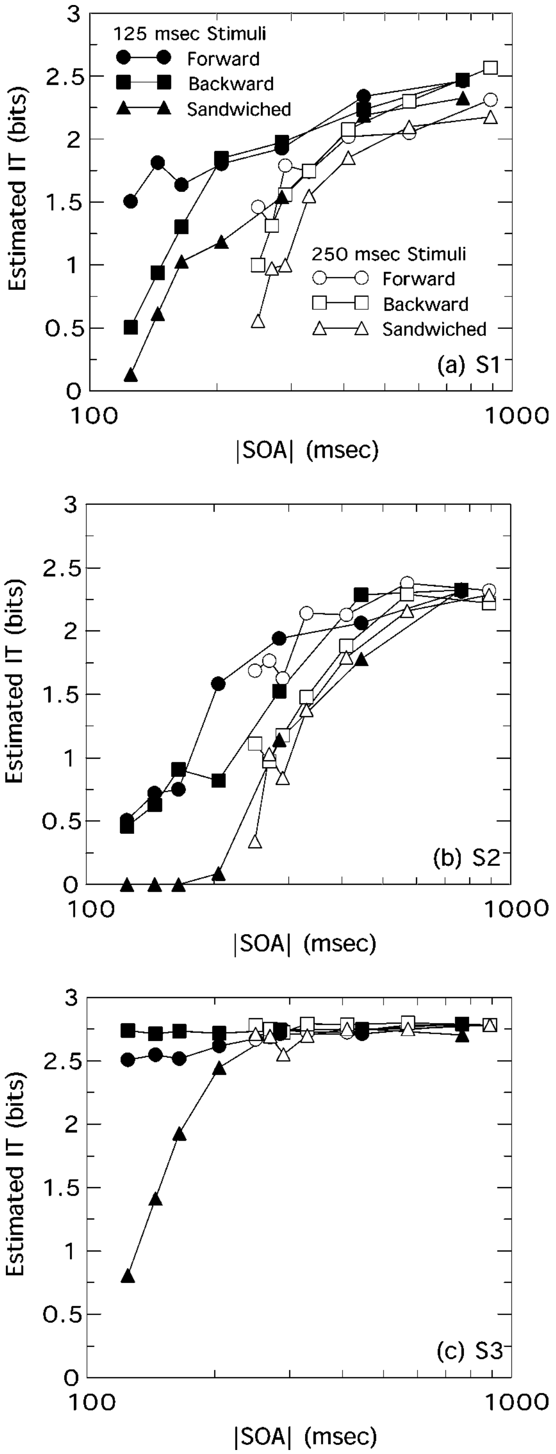


FIG. 3. Estimated IT in bits as a function of |SOA| in ms. Individual-subject data are presented in each of the three panels for 125-ms (filled symbols) and 250-ms (open symbols) stimuli for each of the three masking paradigms: forward (circles), backward (squares), and sandwiched (triangles).

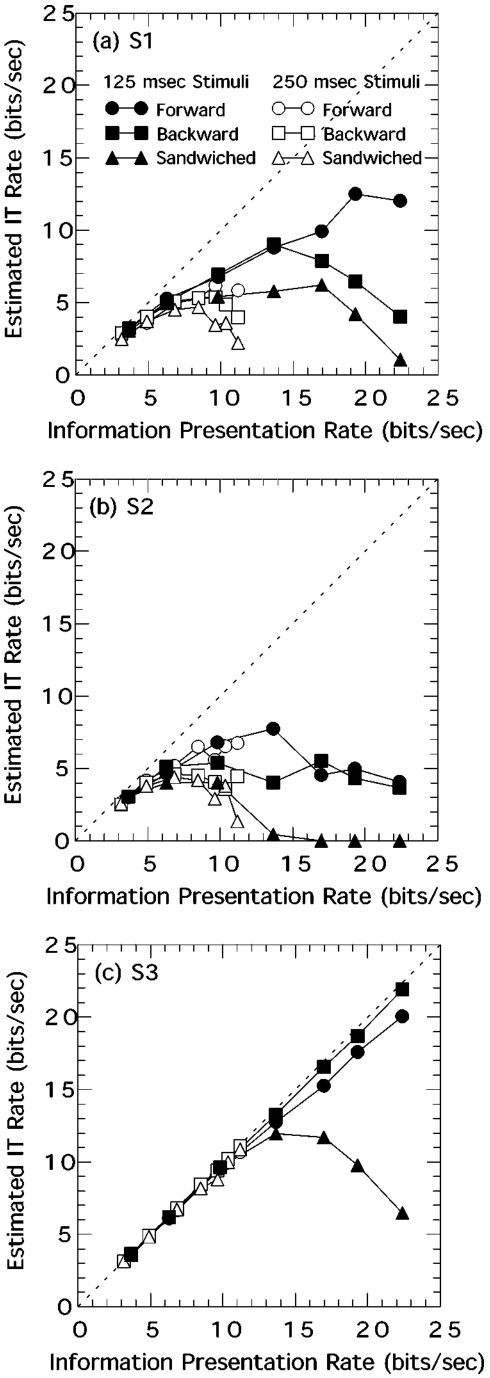


FIG. 4. Estimated IT rate in bits/s as a function of information-presentation rate in bits/s. Individual-subject data are presented in each of the three panels for 125-ms (filled symbols) and 250-ms (open symbols) stimuli for each of the three masking paradigms: forward (circles), backward (squares), and sandwiched (triangles). The diagonal dashed line represents the maximum achievable IT rate.

data of S3 in Fig. 4(c) show a striking consistency: IT rate falls on or near the diagonal dashed line except for the sandwiched-masking paradigm at 125 ms at the highest three values of information presentation rate.

Maximum values of IT rate varied across subjects and were achieved at different combinations of masking paradigm and |SOA| across subjects. For the 125-ms stimulus set, S1 reached a maximum IT rate of 12.5 bits/s at |SOA|=145 ms with the forward-masking paradigm. S2 reached a maximum IT rate of 7.72 bits/s at |SOA|=205 ms with the forward-masking paradigm. S3 reached a maximum IT rate of 21.9 bits/s at |SOA|=125 ms with the backward-masking paradigm. For the 250-ms stimulus set, S1 reached a maximum IT rate of 6.2 bits/s at |SOA|=290 ms with the forward-masking paradigm. S2 reached a maximum IT rate of 6.8 bits/s at |SOA|=250 ms with the forward-masking paradigm. S3 reached a maximum IT rate of 11.1 bits/s at |SOA|=250 ms with the backward-masking paradigm. The maximal rate achieved by S1 and S2 falls substantially below the information-presentation rate at the conditions tested. This result differs from that observed for S3, whose peak IT rate (with the exception of sandwiched masking at 125 ms) is limited primarily by the information-presentation rate achieved in the stimulus ensembles.

IV. DISCUSSION

A. Comparison with tactile temporal masking literature

The results obtained in the present study with relatively long-duration, spectrally defined haptic stimuli presented to the index finger can be compared with those obtained from masking studies employing brief spatial or spatiotemporal patterns delivered through cutaneous stimulation of the index finger (e.g., Craig, 1983, 1995, 1998, 2000; Evans and Craig, 1986; Evans, 1987). Under both forward- and backward-masking paradigms, the ability to identify the target signal has been shown to increase monotonically with SOA such that no further increase in performance is observed for SOA greater than 100 ms for backward masking and for SOA greater than roughly 1000 ms for forward masking (e.g., Craig, 1983, 1995; Evans and Craig, 1986). It is also generally accepted in the spatiotemporal masking literature that more backward than forward masking occurs at brief values of SOA (i.e., less than 100 ms) (e.g., Evans, 1987; Evans and Craig, 1986; Gescheider, Bolanowski, and Verrillo, 1989). At the same time, there is evidence to suggest that forward masking occurs over a longer time period than backward masking: although backward-masking effects are complete for SOA of 100–200 ms, forward masking appears to persist for SOAs up to roughly 1 s (Craig and Evans, 1987). As expected, the results of the current study also demonstrate an orderly increase in target-identification ability with SOA (see Fig. 2). Our results, however, do not demonstrate a consistent performance difference between forward and backward masking [except perhaps for the data of S2 at 250 ms (Fig. 2, left panel b) and the data of S1 at 125 ms (Fig. 2, right panel a)]. The amount of forward or backward masking is similar across the range of SOA values tested and appears to be complete within the first 400–500 ms following stimulus onset (Fig. 2).

The results described above for backward- and forward-masking patterns with cutaneous spatial stimuli have been explained in terms of effects associated with the storage of an internal representation of tactile stimuli that persists following their offset. In the case of short values of SOA, the internal representation associated with the target is stronger under forward masking (where the target is the trailing stimulus in the pair) than under backward masking (where it is the leading stimulus). Thus, less masking of the target occurs under forward compared to backward masking at short SOA. At longer values of SOA, however, the internal representation associated with the leading stimulus (the masker in forward masking) appears to persist for hundreds of ms and to interfere with identification of the trailing target. Differences in the relative effects of forward versus backward masking between the current study and previous studies may be due in part to differences in stimulus duration. The stimuli employed in the current study were relatively long in duration (125 or 250 ms, in order to accommodate low-frequency signals at 2 and 4 Hz) compared to the 26-ms duration used in many of the Optacon-based studies. For the relatively long stimulus durations (leading to relatively long SOA values) employed here, a strong internal representation of the target may be established whether the target is the leading or trailing stimulus in the pair, thus explaining the similarity in performance between forward and backward masking. The smallest SOA employed in the current study was 125 ms (associated with the 125-ms stimulus set and ISI=0 ms), which exceeds the 100-ms time window under which tactile masking effects appear to be the strongest.

The heterogeneous frequency composition of the stimuli employed here also likely plays a role in explaining differences between the current results and those of previous studies employing strictly cutaneous stimulation. From a neurophysiological point of view, the slowly adapting type 1 system (SA I), the rapidly adapting system (RA), and the Pacinian system (PC) are most sensitive to stimulation in the F_L, F_M, and F_H frequency ranges, respectively (Bolanowski *et al.*, 1988; Johnson *et al.*, 2000). Each of these systems is known to exhibit different temporal and spatial summation properties, thus adding complexity to the time course of the ''internal representation'' of these stimuli compared to those employing strictly cutaneous stimulation. The component-response analysis attempted to separate the masking effects of low, mid, and high-frequency components of the stimuli employed in the current study. The results indicated that the low-frequency component F_L in a masker was least likely to be combined with the target to form an erroneous response. This result was consistent with the subjective impression that only the F_M and F_H components tended to ''spread'' in time. The use of F_H in a component response was greater for the 250-ms compared to the 125-ms stimuli and for forward compared to backward masking. Of the three different afferent types of the tactual sensory system, only PC (associated with F_H stimulation) is known to exhibit temporal and spatial summation properties. Such properties may explain why an F_H component in a masker might have been perceived as belonging to a target presented before or after the masker and why this would be more likely to occur with longer-duration stimuli and forward masking. Such temporal/spatial summation properties alone, however, may not be sufficient to explain all the component-response results. Although it is known that neither the RA nor the SA I fibers exhibit temporal or spatial summation (Bolanowski *et al.*, 1988), component responses were observed with F_M as well as with F_H.

Comparisons of error patterns in the current study and previous studies reveal further similarities and differences in the processing of spatiotemporal patterns versus the spectral-based stimuli studied here. Four areas are discussed below, including the role of stimulus complexity in target identification, masker-response competition, temporal integration of

TABLE IV. Percent-correct scores for target patterns (T) containing one, two or three spectral components. Results are averaged across SOAs.

Duration (ms)	Forward masking			Backward masking			Sandwiched masking		
	T has 1 freq.	T has 2 freq.	T has 3 freq.	T has 1 freq.	T has 2 freq.	T has 3 freq.	T has 1 freq.	T has 2 freq.	T has 3 freq.
250	91.1%	85.9%	78.1%	92.2%	83.7%	75.5%	88.5%	81.0%	67.1%
125	89.7%	83.7%	76.6%	88.3%	83.4%	67.4%	79.5%	74.0%	57.9%

masker and target, and performance when target and masking signals are identical.

1. Stimulus complexity

The effects of stimulus complexity on target identification appear to be generally similar for both types of stimuli. For backward masking, Evans (1987) reported that percent-correct scores with one-line target patterns were significantly higher than those with two-line target patterns, indicating that subjects were able to identify simpler spatial patterns more accurately. Similarly, our percent-correct scores were highest with target patterns that contained one spectral component, and lowest with those that contained three spectral components (see Table IV).

2. Masker-response competition

Response competition has been widely studied as the source of errors in temporal masking (e.g., Evans, 1987; Evans and Craig, 1992; Craig and Evans, 1995; Horner, 2000). The rationale for this type of interference is based on the notion that both the target and the masker are fully processed to their respective responses, but that the subject mistakenly chooses the masker response instead of the target response at brief values of SOA. Evans (1987) reported significant use of the masker as the response under backward, but not forward, masking of spatial patterns presented to the index finger. Under backward masking, Evans (1987) observed that roughly 20%–30% of the errors made at SOAs in the range of 26–106 ms could be attributed to the use of the masker as response. Under forward masking, however, the use of the masker as response did not exceed chance levels at any value of SOA. The results of the current study demonstrate substantial use of the masker as response under both backward and forward masking. The rate of masker response on error trials for both types of masking ranged from roughly 15%–30% across SOA for the 250-ms signals and from roughly 20%–40% for the 125-ms signals. The highest rate of responding with the masker was observed for the short-duration stimuli at small values of SOA. One plausible explanation for the masker-response competition lies in the limitation imposed by temporal order discrimination threshold (e.g., Craig and Baihua, 1990).

3. Temporal integration of target and masker

The role of temporal integration of the target and masker has been widely studied as a potential source of error responses in temporal masking of tactile patterns (e.g., Evans and Craig, 1986; Evans, 1987; Craig and Evans, 1987; Craig, 1996; Mahar and Mackenzie, 1993). Originally proposed for visual masking (Felsten and Wasserman, 1980), the temporal-integration theory seems to account for spatiotemporal tactile patterns as well as the spectral-temporal haptic patterns used in the present study. Temporal integration implies that the target and masker form a composite percept that is the temporal and/or spatial sum of both signals. Evans and Craig (1986), in a study of backward masking using tactile spatial patterns, observed an increase in the perceived number of line segments in the response relative to the number in the target for brief SOAs in an identification task and also an overestimation of the number of line segments in the target in an estimation task. Evans (1987) studied the identification of 26-ms spatial patterns under backward and forward masking using a set of 13 line patterns that included stimuli that were composites of two other stimuli in the set. Evidence of use of the composite response on error trials was observed under both backward and forward masking at brief values of SOA (i.e., less than 100 ms): the percentage of composite responses ranged from 20%–70% at the shortest SOA of 26 ms and decreased monotonically as SOA increased. The results of the current study also indicate use of the composite response on error trials, although with some differences in the trends observed by Evans (1987). The rate of composite response observed here ranged from roughly 20%–50% across conditions, did not show a consistent decrease as SOA increased, and was more predominant for the 125-ms compared to the 250-ms signals. Generally, the results from experiments with both tactile and haptic signals provide evidence for the formation of a composite response arising from the properties of the masker and the target.

4. Performance on trials with identical masker and target

Trials with the same stimulus selected for masker and target are of interest based on qualitative predictions from both the response-competition and temporal-integration theories of masking. From both points of view, one would expect that identical stimuli in both intervals of a backward- or forward-masking paradigm should reduce the probability of error. Evans (1987) found very low error rates in the range 1%–4% that did not vary with SOA over trials where target $=$masker under both forward and backward masking. Data from the current experiments, considering only those trials on which target$=$masker, are plotted in Fig. 5. Our results showed a similar trend in that percent scores for trials with identical target and masker were higher than those for all trials. Specifically, the error rates associated with trials with identical target and masker for the forward- and backward-masking paradigms were in the range 3.3% to 10.4% for the

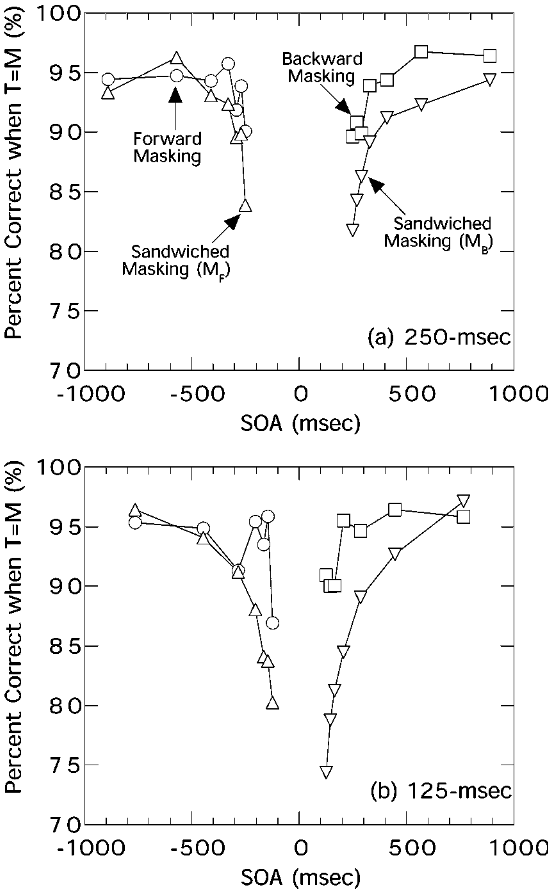


FIG. 5. Percent-correct scores for trials with identical target and masker plotted as a function of SOA (in ms) for 250-ms signals [panel (a)] and 125-ms signals [panel (b)]. Data are pooled across subjects and are plotted for forward (circles), backward (squares), and sandwiched (triangles) masking.

250-ms stimulus set, and in the range 3.6% to 13.1% for the 125-ms stimulus set. These data differ from those of Evans (1987) in that the error rates shown in Fig. 5 do tend to increase with a decrease in SOA. The error rates for the sandwiched-masking paradigm in Fig. 5 were much higher, especially at short SOAs. This higher error rate can be explained by the fact that of all the trials where target=forward masker, only 14.29% (1 out of 7) of the trials contained a backward masker that was identical to the target/forward masker and therefore did not interfere with the identification of the target.

B. Information transmission

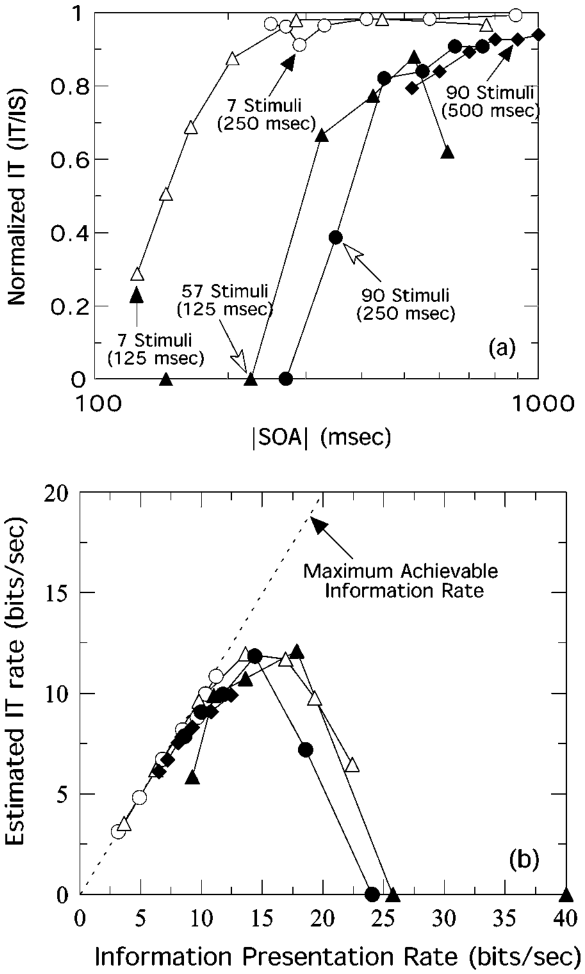


FIG. 6. Comparison of data from five different stimulus sets for subject S3. In panel (a), the normalized IT (i.e., the ratio of estimated IT to IS) is plotted as a function of |SOA| in ms for five different stimulus sets described in the figure. In panel (b), the estimated IT rate in bits/s is plotted as a function of the information-presentation rate in bits/s for the same five stimulus sets. The dashed line plots the maximum achievable IT rate.

The estimates of IT rate from the current study may be compared with those reported by Tan *et al.* (1999) who measured IT and IT rate using the sandwiched-masking paradigm and three different stimulus sets composed of 57 signals at a duration of 125 ms and 90 signals at durations of 250 and 500 ms, respectively. The stimuli employed in the current study represent a subset of the signals from Tan *et al.* (1999). A comparison of the data from the two studies is provided in Fig. 6(a) and Fig. 6(b) for normalized IT (i.e., the ratio of estimated IT to IS, information in stimulus) and IT rate, respectively, for subject S3 who participated in both studies. From Fig. 6(a), it is clear that for a small number of stimulus alternatives (7; see the open symbols), S3's performance approached 100% information transmission at |SOA| values beyond 250 ms. For a large number of stimulus alternatives (57 or 90; see the filled symbols), S3's performance continued to improve even at large |SOA| values. The one datum point for 125-ms stimuli with 57 alternatives at the largest |SOA| value appears to be an anomaly, in that it does not follow the monotonically increasing trend of the rest of the data in Fig. 6(a). As can be seen in Fig. 6(b), S3's performance initially followed the diagonal line of maximum achievable IT rate, reached a peak IT rate, then decreased, as a function of information presentation rate in bits/s. The IT rate for the 90-stimulus set at 500 ms (filled diamonds) and the 7-stimulus set at 250 ms (open circles) seemed to be limited by presentation rate rather than perceptual constraints. One striking trend evidenced in Fig. 6(b) is that performance in terms of IT rate seems to be solely determined by the information presentation rate in bits/s; to a good approximation, all the curves for the different conditions coincide.

The conditions under which maximum IT rate was obtained are tabulated in Table V. The two rates marked with asterisks could potentially be improved if higher information

TABLE V. Optimal SOA, stimulus delivery rate, and the corresponding peak IT rate for data shown in Fig. 6(b). The two rates marked with asterisks seem to be limited by information presentation rate, and can potentially be improved.

Condition	Optimal SOA (ms)	Optimal delivery rate (items/s)	Peak IT rate (bits/s)
7 stimuli (125 ms)	205	4.9	11.9
7 stimuli (250 ms)	250	4.0	10.9*
57 stimuli (125 ms)	325	3.1	12.1
90 stimuli (250 ms)	450	2.2	11.8
90 stimuli (500 ms)	520	1.9	9.9*

presentation rate were used with the corresponding conditions (i.e., in these cases, the normalized IT rate saturated at unity). In general, optimal delivery rate in items/s decreased as stimulus duration increased and as size of the stimulus set (i.e., stimulus uncertainty) increased. On the other hand, the peak IT rate remained remarkably constant across the conditions (around 12 bits/s for the three unmarked values in Table V).

Our results are inconsistent with the generally accepted view that the optimal stimulus delivery rate is between 2 and 3 items/s independent of the stimulus uncertainty (Garner, 1962, p. 91, citing Klemmer and Muller, 1953). In the current study, a constant peak IT rate [see Fig. 6(b) and Table V] of roughly 12 bits/s was obtained independent of stimulus uncertainty in the range of 2.8 to 6.5 bits and independent of stimulus duration over the range 125–500 ms. These results are at variance with the conclusions reached by previous investigators (including Klemmer and Muller, 1953, and Alluisi, Muller, and Fitts, 1957) indicating that peak IT rate increases monotonically with stimulus uncertainty. A rigorous comparison of the current data with previous results is difficult due to the substantial differences in methodology that exist among the relevant studies and is beyond the scope of the current paper. These differences include stimulus modality, type of motor response required of the subject, relationship between signal duration and presentation rate, whether or not response time is taken into consideration in determining the IT rate, as well as values of stimulus uncertainty and information-presentation rate. Further investigation of the properties that contribute to optimizing IT rate is important not only in connection with the design of improved aids for individuals with sensory impairments, but also in connection with the design of improved displays for normally sensed users of data visualization systems and synthetic environments.

V. CONCLUDING REMARKS

The maximum IT rate of roughly 12 bits/s found in our current study and in that of Tan *et al.* (1999) approaches the typical rates demonstrated by natural tactual communication methods. For example, typical communication rate for the Tadoma method (Reed *et al.*, 1985) employed by experienced deaf–blind individuals is estimated to be 11.2 bits/s (Table I, Reed and Durlach, 1998). Typical IT rate for tactual reception of American Sign Language is estimated to be 11.7 bits/s (Table I, Reed and Durlach, 1998). The 12 bits/s rate is higher than the communication rates demonstrated by any other artificial tactual display, including the Optacon (4.5–9 bits/s), vibrotactile or kinesthetic reception of Morse code (0.9–2.2 bits/s), Vibratese (1.8–3.6 bits/s), and tactual reception of fingerspelling (8.1 bits/s) (see Reed and Durlach, 1998, for derivation of these IT rates and for reference to original studies). One major difference between the Tadoma method and most previous synthetic tactual displays is that a talking face provides a multidimensional information display employing a rich set of signal attributes, as compared to the purely cutaneous stimulation provided by many artificial tactual displays. The Tactuator employed in our studies spans the tactual stimulation continuum from kinesthetic movements to cutaneous vibrations. The multidimensional nature of the signals delivered through this display may be the primary factor responsible for the relatively high IT rate achieved in studies with this device. Future experiments are necessary to examine the extent to which the 12 bits/s rate can be maintained for processing continuous streams of multidimensional tactual signals.

ACKNOWLEDGMENTS

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[1] Our definitions of the terms ''tactile,'' ''kinesthetic,'' and ''tactual'' follow those provided by Loomis and Lederman (1986). The term ''tactile'' refers to information acquired through surface contact factors via cutaneous sensors in the skin (e.g., information on texture obtained by relative stroking motion between skin and object, information obtained from vibratory arrays, etc.). The term ''kinesthetic'' relates to information about finger position, motion, and force obtained via sensors in the internal components of the hand, wrist, and arm such as muscles, joints, and tendons. The term kinesthetic is intended to include proprioceptive, and the term ''tactual'' includes both tactile and kinesthetic.

[2] The structure of the stimulus sets employed in the current study may be considered, in some respects, a ''spectral'' analog of the spatial-pattern stimuli studied by Evans (1987).

[3] The one exception was that subject S3 performed only three 100-trial runs for the forward 250 ms condition, because his performance level was near perfect.

[4] ISI values, not SOAs, were used in ANOVA analyses, because ISIs were identical for the two stimulus durations. Given the one-to-one correspondence between the ISI and SOA values, the statistical effects of ISI and SOA are equivalent. According to Craig (1983), SOA, rather than ISI, is the primary determinant of temporal interaction between sequentially presented vibrotactile patterns. Therefore, our results are presented as a function of SOA whenever possible.

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