Modality-specific differences in the processing of spatially, temporally, and spatiotemporally distributed information

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Modality-specific differences in the processing of spatially, temporally, and spatiotemporally distributed information

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Abstract. The extent to which auditory, tactile, and visual perceptual representations are similar, particularly when dealing with speech and speech-like stimuli, was investigated. It was found that comparisons between auditory and tactile patterns were easier to perform than were similar comparisons between auditory and visual stimuli. This was true across a variety of styles of tactile and visual display, and was not due to limitations in the discriminability of the visual displays. The findings suggest that auditory and tactile representations of stimuli are more alike than are auditory and visual ones. It was also found that touch and vision differ in terms of the style of information distribution which they process most efficiently. Touch dealt with patterns best when the pattern was characterised by changes across time, whereas vision did best when spatially or spatiotemporally distributed patterns were presented. As the sense of hearing also seems to specialise in the processing of temporally ordered patterns, these results suggest one way in which the senses of hearing and touch differ from vision.

1 Introduction

In his review of tactile speech prostheses Sherrick (1984) raised the general issue of the extent to which touch has the capacities required to process speech transforms, and the specific issue of whether similarities exist between auditory and tactile sensory processes which allow a mapping of acoustic events into the tactile domain. Similar questions may also be asked regarding the relationship between hearing and vision—a modality which has also been employed to present speech transforms. The research reported here addressed these questions by exploring the extent to which auditory, tactile, and visual perceptual and cognitive processes are alike, particularly when dealing with stimuli like those presented by some current speech prostheses.

Békésy (1955, 1959) found several mechanical and perceptual similarities between hearing and touch in the processing of vibrations. Thus, an obvious question is whether both modalities deal with the parameters of vibrations (amplitude and frequency) in similar ways. Although both senses respond to changes in the frequency of vibrations, it is only at frequencies below about 100 Hz that tactile and auditory frequency acuity is comparable (Goff 1967). This seems due to differences in the frequency-coding mechanisms operating in each modality. Below 100 Hz both modalities encode frequency by rate of neural discharge, whereas at higher frequencies hearing encodes frequency by place of maximum displacement of the basilar membrane (Békésy 1956, 1957; Gulick 1971).

The ear and the skin both respond similarly to changes in the amplitude of vibrations. Increasing the amplitude of vibrations presented either to the ear or to highly innervated cutaneous regions leads to a similar growth in perceived intensity (Békésy 1958; Stevens 1959a). Subjects can also accurately match the amplitudes of vibrations presented to each modality (Stevens 1959b).
Granted the similarities between hearing and touch in terms of the way in which they process vibratory stimuli, it might be expected that these stimuli are represented and processed in similar ways at the perceptual and cognitive levels. Handel and Buffardi (1968) have shown that there may be some fundamental similarity between auditory and tactile percepts. Their subjects viewed sequential patterns whose elements were identified by their modality of presentation. When the respective pattern elements were either tactile and visual, or visual and auditory, the subjects learnt to identify the pattern more rapidly than when the respective elements were auditory and tactile. Thus the subjects had difficulty differentiating between auditory and tactile models of stimulation, but not between auditory and visual or between tactile and visual inputs. Indeed, the subjects reported a sensation of “snapping back and forth between modalities” (Handel and Buffardi 1968, page 1028) in the latter cases, but not when auditory and tactile stimuli were paired.

Although these observations show that some vibrotactile and auditory stimuli yield similar percepts, which differ from those arising from some visual stimuli, the generality of this observation is not clear. For example, would Handel and Buffardi (1968) have achieved the same results if the respective visual and tactile stimuli had been geometric shapes rather than coloured lights and vibrations? Perhaps these conditions would show the tactile and visual representations of the stimuli to be most alike. Of particular relevance here is whether tactile and auditory representations of speech-derived stimuli are similar. Eilers et al.’s (1988) demonstration of equivalent perceptual changes in either modality in response to changes in spectral characteristics of speech stimuli suggests that such similarities do exist.

Handel and Buffardi (1968) found similarities between auditory and tactile perceptual representations of patterns, and differences between these and visual representations, but they did not use speech stimuli. Similarly, although Eilers et al.’s (1988) data indicate that tactile and auditory representations are similar when speech stimuli are used, these authors did not include a visual transform condition. Hence the degree of similarity between tactile, visual, and auditory representation of speech-derived stimuli still requires clarification. The first three experiments reported here address this by investigating the ease with which visual and tactile representations of speech and speech-like stimuli can be compared with equivalent auditory stimuli. The final three experiments focused more closely on a potential difference between hearing, touch, and vision; that is, the way in which spatially and temporally distributed information is processed within each of these modalities.

2 Experiment 1: Comparisons between auditory, tactile, and visual representations of spoken words

In experiment 1 we attempted to extend the results of Handel and Buffardi (1968) and Eilers et al (1988) by requiring subjects to compare speech-derived stimuli presented to hearing, touch, and vision. If greater similarities exist between hearing and touch than between hearing and vision then it was expected that comparisons between auditory and tactile representations of spoken words would be performed better than would equivalent comparisons between auditory and visual stimuli. This prediction was based on the assumption that comparisons between similar types of perceptual representation are performed both faster and more accurately than are comparisons between less-similar representations. Support for this design comes from cross-modal and intra-modal matching studies which have shown that the process of translation from one modality to another imposes a penalty in terms of speed and accuracy (Bjorkman 1967; Ittyerah and Broota 1983).
The hypothesis was operationalised via a task measuring the speed and accuracy with which subjects compared the pattern of stress in two-syllable spoken words with that in subsequently presented auditory, tactile, or visual representation of two-syllable spoken words. Stress pattern was chosen as the target-stimulus parameter because it is a feature useful in speech perception (Plant 1983), and because the amplitude-envelope information necessary to represent syllable stress can be provided without recourse to complex multichannel tactile displays.

2.1 Method

2.1.1 Subjects. Thirty university undergraduates with normal or corrected-to-normal visual and auditory acuity participated in this experiment.

2.1.2 Apparatus and procedure. Each subject was presented with 78 randomly ordered pairs of two-syllable spoken words. One third of the pairs consisted of identical words, one third consisted of different words stressed on the same syllable, and the remainder consisted of words stressed on different syllables. Within each word-pair type, an equal number of words were stressed on either syllable. The words included in each set were matched for word frequency in the Kucera-Francis Word Index (Kucera and Francis 1967). All the word pairs were recorded on audiotape and checked by three observers to ensure that they were stressed correctly.

The first word in each pair (the reference word) was presented directly to the subjects via headphones, and the second word (the target word) was presented 1 s later as either an auditory, a tactile, or a visual transform. In the speech condition the target word was presented directly via headphones. In the envelope condition the target word was presented via headphones as a 1 kHz pure tone modulated in amplitude to mirror changes in the loudness of the word. In the tactile condition the target word was presented as a 250 Hz vibration modulated in amplitude to mirror changes in loudness in the spoken word. These tactile stimuli were presented via a Minivib I single-channel tactile aid with the transducer affixed to the wrist of the subject's preferred arm. The acoustic output of the transducer was attenuated by placing the subject's arm in an acoustically damped box and by the headphones which the subject wore throughout the experiment.\(^1\)

Two types of visual transform were used. In the visual condition a graphical representation of amplitude changes within the spoken words was presented on a cathode ray oscilloscope. These stimuli were generated in real-time across the screen so that by the end of each trial the entire representation of the target word was visible. This display was intended to reflect a simple version of the spectrograph display used in previous attempts to convey speech transforms visually (Potter 1945; Potter et al 1947). Finally, in the print condition, the target word was presented as text on a VDU under microcomputer control.

Each subject was randomly allocated to one of the five comparison conditions. The subjects undertook 18 practice and 60 experimental trials during which they indicated whether the pattern of stress in the two words was the same or different via a two-choice button press. Response latency and accuracy were recorded, with the subjects instructed to respond as rapidly as possible without compromising accuracy. Feedback on response accuracy was provided after each trial.

\(^1\) The need to present spoken words to the subjects prevented the use of a more sophisticated control such as acoustic masking. However, no subject reported being able to hear the vibrators in the current experiment.
2.2 Results and discussion

Mean response latencies and accuracies are presented in table 1 as a function of target-word modality and word-pair type. In the case of accuracy, ANOVA revealed a significant effect due to target-word modality \((F_{4,25} = 27.3, p < 0.001)\), a significant effect due to word-pair type \((F_{2,50} = 28.51, p < 0.001)\), and a significant interaction between these two factors \((F_{8,50} = 2.55, p < 0.05)\). Analysis of reaction-time means also revealed significant effects due to target-word modality \((F_{4,25} = 4.52, p < 0.01)\), word-pair type \((F_{2,50} = 29.76, p < 0.001)\), and a significant interaction between these factors \((F_{8,50} = 4.86, p < 0.001)\).

A posteriori analysis via Tukey's test revealed that the effects of target-word modality on response speed and accuracy were primarily because of poor performance in the visual condition. This task was performed significantly slower and less accurately than were the speech, tactile, or print tasks. None of the other comparisons revealed significant differences in terms of response speed, but both the tactile and the envelope tasks were performed significantly less accurately than were either the speech or print tasks.

In the case of the significant effects of word-pair type on response speed and accuracy, similar a posteriori tests revealed that comparisons between identical words were performed significantly faster and more accurately than were comparisons involving either same-stress or different-word pairs. Finally, comparisons between same-stress word pairs were found to be performed significantly faster and more accurately than comparisons involving different-word pairs.

A posteriori analysis of reaction-time cell means via Tukey's test revealed that the interaction between target-word modality and word-pair type was due to a difference in the speed with which identical and same-stress word pairs were compared both in the speech and in the print conditions and performance in the other three conditions. Identical word pairs were compared significantly faster than were either same-stress or different-word pairs only in the speech and print conditions. The nature of the interaction was less clear cut in the case of accuracy cell means. In the envelope, tactile, and print conditions comparisons between different-word pairs were performed

<table>
<thead>
<tr>
<th>Target-word modality</th>
<th>Reaction time/s</th>
<th>Accuracy (proportion correct)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>word-pair type</td>
<td></td>
</tr>
<tr>
<td></td>
<td>identical</td>
<td>same stress</td>
</tr>
<tr>
<td>Speech</td>
<td>0.95</td>
<td>(0.35)</td>
</tr>
<tr>
<td>Envelope</td>
<td>1.64</td>
<td>(0.35)</td>
</tr>
<tr>
<td>Tactile</td>
<td>1.33</td>
<td>(0.31)</td>
</tr>
<tr>
<td>Visual</td>
<td>1.95</td>
<td>(0.43)</td>
</tr>
<tr>
<td>Print</td>
<td>0.86</td>
<td>(0.30)</td>
</tr>
<tr>
<td>Mean</td>
<td>1.34</td>
<td>(0.53)</td>
</tr>
</tbody>
</table>
significantly less accurately than were comparisons between identical word pairs. With
the exception of the envelope condition, different-word pairs were compared no less
accurately than were same-stress word pairs. Finally, no significant differences in
the accuracy with which each word-pair type was compared were found in either the
speech or the visual conditions.

Although the poor performance observed in the visual condition is consistent with
the hypothesis that auditory-to-visual comparisons are more difficult than are auditory-
to-tactile comparisons, the good performance observed in the print condition challenges
this conclusion. The nature of the interaction between target-word modality and
word-pair type in the case of response latency suggests one way in which this conflict
may be resolved, and indeed a potential limitation on the use of spoken or printed
words as stimuli in this type of study.

Whereas subjects in the speech and print conditions could access the lexical identity
of all the words presented, this was not so in the case of the target words in the other
conditions. Thus, speech and print subjects could compare identical words simply by
establishing their lexical identity but would have to employ a more complex strategy
for same-stress and different words. Conversely, subjects in the other conditions
would have to perform all comparisons via a direct analysis of the pattern of amplitude
within each target word. If these various strategies differ in efficiency then this may
account for the observed interactions between target-word modality and word-pair type.

In this case, performance in the speech and print conditions no longer reflects the
ability of the modalities to process physical characteristics of the stimuli, as was
entailed in the other three conditions. As the reference word in each word pair was
also presented directly as speech, the use of a lexically based strategy to determine
the stress pattern in these words also challenges the relevance of the data in all
conditions to the ability of each modality to deal with physical characteristics of the
stimuli.

3 Experiment 2: Comparisons between nonlexical representations of spoken words

Although the results in experiment 1 suggested that auditory and tactile perceptual
representations are more alike than are auditory and visual ones, it was also found
that subjects may not judge the stress patterns of spoken words via a direct analysis
of amplitude changes in the stimuli. In experiment 2 we attempted to confirm the
cross-modal comparison results from experiment 1 when the subjects were forced to
perform a direct analysis of the amplitude patterns in all stimuli.

3.1 Method

3.1.1 Subjects. Twenty undergraduate volunteers with normal or corrected-to-normal
hearing and vision participated in this experiment.

3.1.2 Apparatus and procedure. The audiotaped stimuli used in experiment 1 were
 retained here, as were the tactile and visual comparison conditions. However, the
reference word in each word pair was now presented as a 1 kHz pure tone modulated
in amplitude to mirror momentary changes in the amplitude envelope of the words.
This type of stimulus required the subjects to perform a direct analysis of the stress
pattern in each word in all conditions, thus removing the confounding effects of a
lexically based strategy. Consequently, the speech condition from experiment 1 was
replaced with a condition when both the reference and the target words were pre-
sented as speech-envelope representations. Granted the issue of lexical access, the
print condition was dropped. Each subject undertook 18 practice and 60 experi-
mental trials in one of these three comparison conditions. The procedure followed
was the same as that for experiment 1.
3.2 Results and discussion
As we were concerned in this experiment with differences due to target-word modality rather than differences due to word-pair type, the reaction-time and accuracy data were pooled across word-pair types yielding the means presented in table 2. Whereas auditory-to-auditory and auditory-to-tactile comparisons were performed faster than were auditory-to-visual comparisons, accuracy levels were similar across all three conditions.

Analysis via ANOVA confirmed that reaction times differed significantly as a function of target-word modality ($F_{2,12} = 20.82, p < 0.001$). A posteriori analysis via Tukey’s test revealed that this was due to the visual task being performed significantly more slowly than the other two tasks. Accuracy did not differ significantly as a function of target-word modality ($F_{2,12} = 1.67, p > 0.05$).

In summary, although the auditory-to-visual comparisons were performed as accurately as were the other types of comparison, this task was performed more slowly than either the auditory-to-auditory or auditory-to-tactile comparisons. As pilot studies had revealed that the visual display was no less discriminable than were the auditory and tactile displays, these difficulties must have arisen at the time that the cross-modal comparisons were made, rather than when the subjects were extracting information about the stress patterns of each word from the individual displays.

Of course these results do not show that tactile transforms of speech are unequivocally easier to compare with auditory stimuli than are their visual equivalents. Other tactile transforms may be less efficient, with other visual ones being more efficient, than those used in this experiment. All that can be said with certainty is that this particular tactile display was easier to compare with the auditory one than was this specific visual display.

One factor which may have impeded performance with the visual display was the style of display used in the various modalities. In particular, the subjects were asked to compare spatiotemporal arrays of visual stimuli with temporal arrays of auditory stimuli, in which case any cross-modal effects may have been confounded with cross-information distribution-style effects (Freides 1974; Sawada and Jarman 1982; Sterritt and Rudnick 1966). For example, Bryden (1972) found that comparisons across both modality and information-distribution style are more difficult to perform than are comparisons across modality but within information-distribution style. As the present auditory and tactile stimuli were distributed purely across time, whereas the visual stimuli varied across both time and space, the poor performance in the auditory-to-visual comparison condition might have resulted from this cross-information distribution-style factor rather than from differences in the compatibility of the modalities. With these possibilities in mind, in experiment 3 we assessed whether the poor performance observed in auditory-to-visual comparisons was due, as Bryden’s (1972) data suggest, to an incompatibility between the styles of information distribution presented to each modality.

Table 2. Mean reaction times for correct responses and mean accuracy scores from experiment 2 as a function of target-word modality. Standard deviations are given in parentheses.

<table>
<thead>
<tr>
<th>Target-word modality</th>
<th>Reaction time/s</th>
<th>Accuracy (proportion correct)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Envelope</td>
<td>1.18 (0.32)</td>
<td>0.74 (0.05)</td>
</tr>
<tr>
<td>Tactile</td>
<td>1.35 (0.19)</td>
<td>0.75 (0.07)</td>
</tr>
<tr>
<td>Visual</td>
<td>2.29 (0.34)</td>
<td>0.68 (0.06)</td>
</tr>
</tbody>
</table>
4 Experiment 3: Cross-modal comparisons and information-distribution style

This experiment was modelled on the general design of experiments 1 and 2, except that synthetic representations of two-syllable words were used instead of direct transforms of actual words, and temporally, spatially, and spatiotemporally distributed tactile and visual target displays were included. The visual stimuli now consisted of pairs of bars differing in luminance, and the tactile and auditory stimuli consisted of vibrations varying in amplitude. These systematic variations in luminance or amplitude provided an analogue of the amplitude differences between the two syllables of the words used in the previous experiments. In addition to this change, all possible attempts were made to ensure that the temporally, spatially, and spatiotemporally distributed displays used in each modality differed only in terms of those characteristics entailed in that style of display. It was hoped that the addition of these extra controls over the nature of the stimuli would allow a clearer assessment of the reasons for any within-modality or between-modality differences in performance.

4.1 Method

4.1.1 Subjects. Forty university undergraduates with normal or corrected-to-normal hearing and vision participated in this experiment.

4.1.2 Apparatus and procedure. The subjects' task was to compare either a visual or a tactile target stimulus with a subsequently presented auditory reference stimulus. The reference stimuli were pairs of sequentially presented auditory pulses. Each pulse was a 550 ms duration 1 kHz ramp-wave tone with a 300 ms interstimulus interval (ISI) between the two pulses in each pair. The amplitude of the two pulses in each pair was manipulated to provide a simple analogue of the amplitude-envelope representations of two-syllable words presented in the earlier experiments. The amplitude of the louder pulse in each pair was either 33, 30, 27, or 24 dBm (2) with that of the quieter pulse being set 6 dBm lower. The pulses were generated by an Applied Engineering Super Music Synthesiser controlled by a microcomputer, and were presented binaurally via Senheiser HD22 headphones.

The tactile target stimuli consisted of pairs of 250 Hz ramp-wave vibrations presented via Oticon bone-conduction hearing aids placed under the index and third fingertips of the subject's preferred hand. These signals were generated by an Applied Engineering Super Music Synthesiser controlled by a microcomputer. The amplitude of the two vibrations in each pair was varied in the same way as in the case of the auditory pairs, with the exception that the lower sensitivity of touch necessitated a difference of 9 dBm between the strong and weak pulses in each pair. Again the acoustic output of the vibrators was controlled both by placing the subject's hand into an acoustically damped box and by the attenuation provided by the headphones used to present the auditory stimuli.

There were four tactile-to-auditory comparison conditions. In the tactile-temporal condition the first vibration was presented simultaneously to both fingertips for 550 ms and after a 300 ms ISI there was a second vibration presented simultaneously to both fingertips for 550 ms. In the tactile-spatial condition the two vibrations were presented simultaneously for 550 ms to the first and third fingers. In the tactile-spatiotemporal condition the first vibration was presented for 550 ms to the index fingertip and after a 300 ms ISI there was a second vibration presented for 550 ms to the third fingertip.

Owing to the sequential presentation method used in the tactile-temporal and tactile-spatiotemporal conditions, it was possible for the subjects to process the first

(2) 0 dBm is equivalent to 1 mW into a 600 ohm resistive load.
vibration in each pair before the second vibration was presented. As the simultaneous-presentation method used in the tactile-spatial condition precluded the subjects from preprocessing the first vibration, it was feared that this would impede performance on this task relative to performance on those tasks where the first vibration could be preprocessed. To test for this preprocessing effect, a second tactile-spatial condition was included in which an additional delay of 850 ms (equivalent to the duration between the onset of the two vibrations in the tactile-temporal and tactile-spatiotemporal conditions) was included after the termination of the display before the auditory reference stimulus was presented. It was expected that this extra processing time available in the tactile-spatial-delayed condition would compensate for any preprocessing advantage inherent in the other two conditions.

The visual target stimuli were pairs of luminous bars generated by a Sprite Graphics card controlled by a microcomputer and displayed on a Sony CVM110 VDU. These bars were varied in luminance to provide a visual analogue of the auditory reference stimuli. The luminance of the high-intensity bar in each pair was set at either 125, 116, 98, or 67 cd m\(^{-2}\), with the corresponding low-intensity bar being set at either 116, 98, 67, or 51 cd m\(^{-2}\), respectively. Each bar extended across 3.30 deg of visual field with a height of 0.75 deg of visual field.

Four different visual presentation methods were used. In the visual-temporal condition the two bars were presented sequentially at the centre of the screen. Each bar was displayed for 550 ms with a 300 ms ISI. In the visual-spatiotemporal condition the first bar was presented for the duration of the display on the left-hand side of the screen. The second bar was then presented for 550 ms on the right-hand side of the screen, 850 ms after the onset of the first bar. In the visual-spatial condition both bars were displayed side by side on the screen for 550 ms. Finally, the visual-spatial-delayed condition was identical to the visual-spatial condition except that an additional delay of 850 ms was included after the termination of the display and before the presentation of the auditory reference stimulus. As with the tactile-spatial-delayed task, this visual condition was included to control for any preprocessing differences between conditions.

Each subject undertook 12 practice and 48 experimental trials in one of the eight cross-modal comparison tasks. On each trial they were presented with the tactile or visual target stimulus then, after a 100 ms delay (950 ms in the cases of the tactile and visual spatial-delayed conditions), with the auditory reference stimulus. Their task was to identify whether the same pulse was most intense in the target and reference display and to indicate their response on a two-choice button press operated with their nonpreferred hand. They were told to respond as quickly as they could without sacrificing accuracy. Reaction-time and accuracy data were recorded, with reaction timing commencing at the onset of the auditory reference display. This ensured that there was a constant delay between the onset of timing and the termination of the trial, regardless of the target-stimulus presentation method.

4.2 Results and discussion
The mean reaction times for correct responses and mean \(d'\) (Green and Swets 1966) scores for each level of each factor in the experiment are presented in table 3. Values of \(d'\) were calculated counting same-intensity pattern pairs which were correctly identified as ‘hits’ and different-intensity pattern pairs which were incorrectly identified as ‘false alarms’. On average, the tactile-to-auditory comparisons were performed faster and more accurately than were the visual-to-auditory comparisons. These trends were confirmed by ANOVA, which showed a significant effect due to target stimulus modality both in accuracy \((F_{1,32} = 7.94, p < 0.01)\) and in reaction-time \((F_{1,32} = 5.93, p < 0.05)\) data.
As further support for the general superiority of tactile-to-auditory comparisons over visual-to-auditory ones, only the tactile-to-auditory comparisons in the tactile-spatiotemporal and tactile spatial-delayed conditions yielded worse scores on either dependent measure than were recorded in the best performed of the four visual-to-auditory comparisons. However, in both these cases it seems that the subjects employed speed/accuracy tradeoffs. Thus it is difficult to conclude that either task was performed less well than any of the visual-to-auditory comparison tasks.

Differences in reaction times and accuracy were also found between the four styles of information distribution within each modality. Whereas this trend was significant in the case of reaction time \((F_{3,32} = 4.25, p < 0.05)\), it did not reach significance in the case of accuracy \((F_{3,32} = 0.11, p > 0.05)\). Finally, although no significant interaction between target-stimulus modality and information-distribution style was found in the case of accuracy \((F_{3,32} = 1.65, p > 0.05)\), a significant interaction between these two factors was evident in the case of response speed \((F_{3,32} = 3.09, p < 0.05)\).

A posteriori comparisons were performed between each style of information distribution within each modality using Fisher’s LSD test to explore this interaction. Only the differences in speed between the tactile-temporal and tactile-spatial-delayed \((t_{32} = 3.19, p < 0.01)\), tactile-spatial and tactile-spatiotemporal \((t_{32} = 2.48, p < 0.05)\), and tactile-spatial-delayed and tactile-spatiotemporal \((t_{32} = 4.27, p < 0.001)\) conditions were significant. Thus the interaction between target-stimulus modality and information-distribution style involved a response-speed deficit between the purely spatial tactile tasks and tasks involving temporally distributed information, which was not evident between these types of visual task. These a posteriori comparisons between reaction-time means, taken with the lack of a significant effect on response accuracy due to information-distribution style, show that the spatial-delayed tasks in both modalities were performed no better than were the spatial tasks. This suggests that the other tasks did not have a preprocessing advantage over the spatial ones.

In general, these results support those of experiments 1 and 2 in showing that tactile-to-auditory comparisons are performed faster and more accurately than are visual-to-auditory comparisons, even when differences in information-distribution style are controlled. This provides further support for the hypothesis that tactile and auditory representations of patterns are more alike than are auditory and visual representations of those patterns. Second, the style of information distribution used in the target displays was found to affect only the speed with which tactile-to-auditory comparisons were performed. Responding was slower in the purely spatial-tactile tasks than in those tasks involving temporally distributed information. Finally, as the tactile spatial-delayed task was performed no better than the tactile-spatial one, it seems that this speed deficit was not due to any preprocessing advantage inherent in the other tactile tasks. As with the earlier cross-modal comparison experiments,

| Table 3. Mean reaction times for correct responses, and mean accuracy scores \((d')\) for tactile and visual tasks in experiment 3. Information distribution was temporal (T), spatial (S), spatial delayed (S-D), or spatiotemporal (S-T). Standard deviations are shown in parentheses. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Response        | Target-stimulus information-distribution style |
| Tactile tasks   | T               | S               | S-D             | S-T             | mean            |
| Reaction time/s | 1.57 (0.11)     | 1.70 (0.16)     | 1.87 (0.15)     | 1.46 (0.08)     | 1.65 (0.20)     |
| Accuracy \((d')\)| 2.24 (0.36)     | 1.84 (0.73)     | 2.12 (0.68)     | 1.59 (0.61)     | 1.95 (0.65)     |
| Visual tasks    | T               | S               | S-D             | S-T             |                 |
| Reaction time/s | 1.17 (0.08)     | 1.74 (0.17)     | 1.81 (0.16)     | 1.80 (0.15)     | 1.77 (0.15)     |
| Accuracy \((d')\)| 1.13 (0.53)     | 1.31 (0.43)     | 1.36 (0.36)     | 1.71 (0.73)     | 1.38 (0.57)     |
an obvious question is whether the observed difference in the ease with which the tactile-to-auditory and visual-to-auditory comparisons were performed was due to differences in the discriminability of the various tactile and visual displays used. This question was explored in experiment 4.

5 Experiment 4: Display discriminability and information-distribution style
This experiment was conducted to assess the ease with which the relative intensity of the two pulses presented in each stimulus pair in experiment 3 could be identified via the various types of display employed in that experiment. If the superior performance observed in the tactile-to-auditory comparison tasks was due to those tactile displays being easier to process than their visual equivalents then it was expected that the more intense pulse in each pair would be identified more rapidly and accurately when presented via the tactile displays.

This experiment also allowed a comparison of the relative ease with which touch and vision deal with information distributed in these three ways—an issue relevant to the general question of ways in which these modalities are more or less alike. The introduction of information-distribution style as a factor in the assessment of similarities and differences between modalities raises the question of whether there are differences in the relative ease with which each modality deals with spatially and temporally distributed information. Indeed, there is evidence that hearing and vision differ in this way.

With respect to spatial and temporal two-point limens, Handel (1988a)(3) and Julesz and Hirsh (1972) noted that hearing has the finer temporal, and vision the finer spatial, resolution. Several studies have also shown that subjects can compare temporally distributed auditory patterns better than visually presented ones (Garner and Gottwald 1968; Gault and Goodfellow 1938; Rubinstein and Gruenberg 1971). At a higher cognitive level, Metcalfe et al (1981) found that subjects can recall the temporal order of auditory stimuli better than spatial order, with the reverse being true in the case of vision. Similarly, it has been shown that subjects have difficulty recalling the location from which spoken words or sentences are presented (Geiselman and Bellezza 1976; Haberlandt and Baillet 1977); results which suggest that spatially distributed aspects of spoken words are not normally a significant factor in speech perception. Finally, O'Connor and Hermelin (1972) found that auditory presentation appears to encourage temporal processing, whereas visual presentation promotes spatial processing.

In the case of touch, threshold studies have shown that the spatial and temporal resolutions of the skin lie between those of hearing and vision (Kirman 1973). However, no previous studies have directly investigated the relative efficiency with which spatially and temporally distributed information is processed by the sense of touch. It has been found that tracing out the elements of alphabetic characters via Optacon-type displays leads to superior levels of performance than does presenting the whole representation at once (Beauchamp et al 1971; Saida et al, cited in Loomis 1981), a result which clearly suggests that tactile perception is impeded if information is presented in a purely spatially distributed form.

In summary, temporally distributed information seems to be processed better by hearing than by vision in threshold and suprathreshold tasks. Conversely, vision processes spatially distributed information better than does hearing in threshold tasks. Likewise, hearing processes temporally distributed information more efficiently than it processes spatially distributed information both in threshold and in suprathreshold

(3) Handel (1988a, 1988b) argued that differences in auditory and visual spatial and temporal acuity are not relevant to whether hearing and vision are either spatial or temporal domains. His argument is considered in detail in section 8.
tasks, with the reverse being true in the case of vision. The limited tactile data available suggest that touch may, like hearing, be better suited to processing temporally distributed information.

Thus, in addition to testing the results of experiment 3, in the present experiment we also explored the way in which vision and touch deal with differences in information-distribution style. If touch, like hearing, deals best with temporally distributed information then it was expected that subjects would respond faster and more accurately when the tactile stimuli were presented temporally rather than spatially. Conversely, if vision prefers spatially distributed information then performance in the visual conditions was expected to be faster and more accurate when the stimuli were presented spatially rather than temporally.

5.1 Method

5.1.1 Subjects. Twelve subjects participated in this experiment. All were undergraduate volunteers with normal or corrected-to-normal visual acuity.

5.1.2 Apparatus and procedure. The stimuli used in this experiment were the same as the spatial, temporal, and spatiotemporal target stimuli used in experiment 3, and were presented in the same way. Each subject undertook 12 practice and 48 experimental trials with each of the six types of display. The order in which the subjects undertook each task was counterbalanced. On each trial the subject identified which stimulus was most intense via a two-choice button press. Reaction timing was commenced at the onset of the display in the case of the spatial tasks and at the onset of the second stimulus in the other tasks. This arrangement ensured that there was a constant delay of 550 ms between the commencement of timing and the termination of the display, regardless of presentation method.

5.2 Results and discussion

Mean reaction times for correct responses and mean accuracy levels ($d'$) for each presentation method are shown in table 4. Whereas the tactile displays were discriminated more accurately than were the visual ones, the reverse applied in the case of response speed. These descriptive observations were confirmed by ANOVA, which revealed a significant effect of presentation modality both on the speed ($F_{1,11} = 8.12, p < 0.05$) and on the accuracy ($F_{1,11} = 6.03, p < 0.05$) of responses. This suggests that the subjects applied different speed/accuracy tradeoff criteria in the visual and tactile conditions. The occurrence of this effect makes it difficult to assess which, if any, presentation modality led to better performance on the task.

It is also clear from table 4 that subjects' performance varied with the style of information distribution employed in the display. This trend was also confirmed by ANOVA, which revealed a significant effect on response accuracy owing to information-distribution style ($F_{2,22} = 5.26, p < 0.05$). The effect of this factor on response speed did not, however, reach significance ($F_{2,22} = 2.67, p > 0.05$).

Table 4. Mean reaction times for correct responses, and mean accuracy ($d'$) for tactile and visual tasks in experiment 4. Information distribution was temporal (T), spatial (S), or spatiotemporal (S-T). Standard deviations are shown in parentheses.

<table>
<thead>
<tr>
<th>Response</th>
<th>Tactile tasks</th>
<th>Visual tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T</td>
<td>S</td>
</tr>
<tr>
<td>Reaction time/s</td>
<td>0.66 (0.14)</td>
<td>0.84 (0.18)</td>
</tr>
<tr>
<td>Accuracy ($d'$)</td>
<td>3.00 (0.79)</td>
<td>1.79 (0.57)</td>
</tr>
</tbody>
</table>
The effects of information-distribution style on the speed and accuracy of responses differed between presentation modalities, as shown by a significant interaction between presentation modality and information-distribution style evident both in the accuracy ($F_{2,22} = 15.76, p < 0.001$) and in the speed ($F_{2,22} = 14.89, p < 0.001$) data. A posteriori simple comparisons revealed that performance in the tactile-temporal condition was significantly faster ($F_{1,11} = 29.87, p < 0.001$) and significantly more accurate ($F_{1,11} = 139.0, p < 0.0001$) than performance in the tactile-spatial condition. For vision, the opposite results were obtained. Responses were significantly faster ($F_{1,11} = 9.08, p < 0.05$) and significantly more accurate ($F_{1,11} = 5.81, p < 0.05$) in the spatial condition than in the temporal condition. In both modalities, spatiotemporal distribution led to similar performance to that found with the preferred information-distribution method. For touch, reaction times for spatiotemporal distribution were not significantly different from those for temporal distribution ($F_{1,11} = 0.85, p > 0.05$) but were significantly shorter than those for spatial distribution ($F_{1,11} = 7.76, p < 0.05$). For vision, the reaction times for spatiotemporal distribution were not significantly different from those for spatial distribution ($F_{1,11} = 0.18, p > 0.05$), but were significantly shorter than those for temporal distribution ($F_{1,11} = 5.44, p < 0.05$). In each case, the results for accuracy mirrored those for speed.

As there was no evidence of subjects employing speed/accuracy tradeoffs within each modality, these results must reflect some differences in task difficulty between conditions. These differences may be attributed to variations in the coding strategy used by each modality, rather than to any procedural differences between presentation methods. The spatial and temporal tasks in each modality differed only in terms of those features which characterised them as being either spatial or temporal in nature: that is being presented at different locations or at different points in time. All other stimulus parameters, such as duration and intensity, were constant across conditions. Further, these distinguishing features were combined in the spatiotemporal tasks, which were performed as well as the 'preferred' tasks in each modality. The presence of 'nonpreferred' information (spatial for touch, temporal for vision) thus did not disrupt efficient processing of the 'preferred' information, but merely led to less efficient processing when it was presented alone.

Several conclusions can be drawn from this experiment. As subjects applied different speed/accuracy tradeoff criteria in the tactile and visual tasks, resulting in superior speed in the visual tasks and superior accuracy in the tactile ones there is no compelling evidence that either mode of display was superior. Thus it cannot be concluded that the superior overall performance on the tactile-to-auditory comparison tasks in experiment 3 was due to limitations in the visual displays used in the visual-to-auditory comparisons tasks. Hence the hypothesis that there is some fundamental incompatibility between the auditory and visual representations of a pattern, which does not exist between auditory and tactile versions, remains the best account of those results.

Second, this experiment revealed differences between touch and vision in the relative ease with which they dealt with temporally, spatially, and spatiotemporally distributed patterns. Visual performance was best when the patterns were distributed either spatially or spatiotemporally, with poorer performance occurring when the patterns were distributed temporally. Differences in performance were also observed between the three styles of tactile display, but the relationship between information-distribution style and performance was different from that in the visual modality. In this case it was the spatially distributed display which was poorly discriminated.

Whereas the greater ease with which tactile-temporal displays were discriminated may have been due to a peculiarity of the displays used, pilot studies showed that this tactile-temporal superiority held over a range of stimulus configurations.
6 Experiment 5: The generality of the touch–time vision–space phenomena

This experiment was conducted to assess whether the results relating to information-distribution style in experiment 4 were artefacts of the particular stimulus dimensions whose variations were to be discriminated. The subjects were again presented with pairs of tactile or visual stimuli, although they now identified which tactile stimulus was higher in frequency or which visual bar was longer. Although these modifications may weaken the analogy between the stimuli and amplitude variations in two-syllable words, they did allow the generality of the effects found in experiment 4 to be assessed. If those effects represent general properties of the tactile and visual modalities, then it was expected that this task would be performed worst in the tactile modality when the pulses were presented spatially, and worst in the visual modality when they were presented temporally.

6.1 Method

6.1.1 Subjects. Twelve undergraduates with normal or corrected-to-normal visual acuity participated in this experiment.

6.1.2 Apparatus and procedure. 48 pairs of tactile or visual stimuli distributed either spatially, temporally, or spatiotemporally were used. Each subject undertook 16 practice and 48 experimental trials in each of these six conditions. The tactile stimuli were ramp-wave vibrations differing in temporal frequency so that one stimulus in each pair was always higher in frequency than the other. The frequency of the high-frequency stimulus in each pair was set at either 300, 500, 700, or 900 Hz with the low-frequency stimulus always being set 200 Hz lower. The amplitude of each stimulus was adjusted to compensate for frequency-specific differences in tactile sensitivity.

These stimuli were presented in the same ways as in experiment 4 with just two exceptions. First, the acoustic output of the vibrators was now masked by 60 dB narrow-band white noise presented for the duration of each session via headphones. Second, the time course of the tactile-spatiotemporal display was altered so that it was identical to that used in the equivalent visual condition. In experiment 4 the second stimulus in this tactile display had been presented 300 ms after the termination of the first stimulus. Now the first stimulus was presented for the duration of the display, with the second stimulus being presented 850 ms after the onset of the first.

The visual stimuli were pairs of luminous bars differing in length. The longer bar in each pair extended across either 2.0, 2.3, 2.6, or 2.9 deg of visual field whereas the shorter bar was always 0.3 deg of visual field shorter than the longer bar. Aside from this modification, these visual stimuli were presented in the same three ways as in experiment 4.

6.2 Results and discussion

Reaction-time and accuracy (d') means for each task are presented in table 5, where it can be seen that the pattern of performance across the three tactile tasks was the same as in experiment 4. The tactile-temporal task was performed both faster (F1,11 = 12.1, p < 0.01) and more accurately (F1,11 = 27.6, p < 0.001) than was the tactile-spatial task. On the other hand, performance on the tactile-spatiotemporal task was not significantly different from that on the tactile-temporal task, either in terms of speed (F1,11 = 2.3, p > 0.05) or of accuracy (F1,11 = 1.3, p > 0.05). As in experiment 4, these results suggest that temporally distributed information is processed more efficiently than is spatially distributed information when the input...
modality is touch. Finally, the changes in the time course of the spatiotemporal display did not change the pattern of results.

The results from the three visual conditions differed somewhat from those of experiment 4. The visual-spatial task was performed faster \((F_{1,11} = 10.7, p < 0.01)\) but no more accurately \((F_{1,11} = 0.25, p > 0.05)\) than was the visual-temporal task. However, the visual-spatiotemporal task was performed more rapidly than either the visual-temporal task \((F_{1,11} = 27.76, p < 0.001)\) or the visual-spatial task \((F_{1,11} = 9.07, p < 0.05)\). However, the visual-spatiotemporal task was not performed significantly more accurately than the visual-temporal \((F_{1,11} = 2.0, p > 0.05)\) or visual-spatial \((F_{1,11} = 3.56, p > 0.05)\) tasks.

These findings again show that vision processes spatially distributed information more efficiently than it does temporally distributed information, in that the spatial task was performed faster than the temporal task with no penalty in terms of accuracy. However, contrary to the results of experiment 4, the visual-spatiotemporal task was performed faster than the visual-spatial one with no penalty in terms of accuracy. The similarity in performance between the visual-spatial and visual-spatiotemporal tasks and between the tactile-temporal and tactile-spatiotemporal tasks in experiment 4 suggested that the presence of nonpreferred information did not affect the processing of preferred information in either modality. The superior visual processing of spatiotemporally distributed displays in the present experiment shows that this effect does not always occur. Instead, vision seems able to attend both to spatially and to temporally distributed aspects of a display, gaining a performance advantage as a result.

**Table 5.** Mean reaction times for correct responses, and mean accuracy \((d')\) for tactile and visual tasks in experiment 5. Information distribution was temporal \((T)\), spatial \((S)\), or spatiotemporal \((S-T)\). Standard deviations are shown in parentheses.

<table>
<thead>
<tr>
<th>Response</th>
<th>Tactile tasks</th>
<th>Visual tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T</td>
<td>S</td>
</tr>
<tr>
<td>Reaction time/s</td>
<td>0.90 (0.25)</td>
<td>1.19 (0.32)</td>
</tr>
<tr>
<td>Accuracy ((d'))</td>
<td>1.63 (0.74)</td>
<td>0.16 (0.35)</td>
</tr>
</tbody>
</table>

7 Experiment 6: Clarification of the visual data from experiments 4 and 5

Experiment 6 was conducted to clarify the divergent results of experiments 4 and 5 concerning the relative ease with which vision processes spatiotemporally distributed information. The visual-spatiotemporal tasks in each experiment differed only in terms of the particular stimulus dimension that was compared, that is either luminance or length. In this experiment, a third stimulus dimension was manipulated to gather evidence concerning the generality of the visual-spatiotemporal data from these earlier experiments. In addition, the design of the present experiment allowed a further confirmation that vision processes spatially distributed information better than it does temporally distributed information. With these aims, the three visual tasks used in the previous two studies were repeated with the modification that the stimuli now differed in spatial frequency rather than in luminance or length.

7.1 Method

7.1.1 Subjects. Eighteen subjects with normal or corrected-to-normal visual acuity participated in this experiment.
7.1.2 Apparatus and procedure. The equipment and procedure used in this experiment were similar to those used in the visual tasks in experiments 4 and 5, with the exception that subjects were now presented with pairs of square-wave gratings differing in spatial frequency. Their task was to identify which grating was lower in spatial frequency. Each grating extended across 2.8 deg of visual field with a height of 3.0 deg of visual field. In the spatial and spatiotemporal distribution conditions the two gratings were separated by 1.0 deg of visual field. The low-frequency grating in each pair had a spatial frequency of either 1.96, 3.03, 3.40, or 5.17 cycles deg\(^{-1}\), whereas the corresponding high-frequency grating had a spatial frequency of either 3.03, 3.40, 5.17, or 10.53 cycles deg\(^{-1}\), respectively. Because of the way in which these displays were generated it was no longer possible to present the subjects with either trial-commencement or feedback messages via the VDU. Instead, the subjects were presented with a warning tone via headphones to indicate the onset of each trial. No feedback was given.

7.2 Results and discussion
Mean reaction times and \(d'\) scores for each task are presented in table 6. As can be seen, these results were similar to those obtained in experiment 5. A series of planned comparisons revealed that the visual-spatial task was performed both faster \(F_{1,17} = 4.79, p < 0.05\) and more accurately \(F_{1,17} = 9.55, p < 0.01\) than was the visual-temporal task. This finding again confirms the superiority of spatial distribution over temporal distribution in visual processing. The visual-spatiotemporal task was performed significantly faster \(F_{1,17} = 29.31, p < 0.001\), although not significantly more accurately \(F_{1,17} = 0.63, p > 0.05\), than the visual-spatial task. Finally, the visual-spatiotemporal task was performed both faster \(F_{1,17} = 13.48, p < 0.01\) and more accurately \(F_{1,17} = 11.58, p < 0.01\) than the visual-temporal task. The consistency of these results with those obtained in experiment 5 suggests that vision may frequently take advantage both of spatially and of temporally distributed information available in spatiotemporal displays.

Table 6. Mean reaction times for correct responses, and mean accuracy \(d'\) in experiment 6. Standard deviations are shown in parentheses.

<table>
<thead>
<tr>
<th>Response</th>
<th>Information-distribution style</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>temporal</td>
</tr>
<tr>
<td>Reaction time/s</td>
<td>0.6 (0.20)</td>
</tr>
<tr>
<td>Accuracy (d')</td>
<td>3.06 (0.57)</td>
</tr>
</tbody>
</table>

8 General discussion
8.1 Differences in the compatibility of auditory, tactile, and visual representations
Experiments 1, 2, and 3 demonstrated that comparisons between auditory and tactile stimuli are easier to perform than are comparisons between auditory and visual stimuli. This was true both in the case of speech-derived and synthetic patterns, and did not appear to depend upon the format in which the stimuli were presented to the tactile and visual modalities.

As the visual stimuli were as discriminable as those presented to touch or hearing, these differences in the ease with which visual and tactile stimuli were compared with auditory ones must have arisen at the time the perceptual representations in each modality were compared. The most parsimonious explanation for this is that they are less alike than are auditory and tactile ones. This conclusion is consistent with previous demonstrations that comparisons between different modes of perceptual
representation impose a penalty in terms both of speed and of accuracy of judgment (Bjorkman 1967; Ittyerah and Broota 1983). Finally, the greater experience which subjects typically have in dealing with auditory and visual stimuli than with vibrotactile ones suggests that this auditory-to-tactile comparison superiority is not due to differences in stimulus familiarity.

With respect to the applied issue of the design of nonauditory prostheses for the profoundly deaf, these results suggest that tactile prostheses may enjoy a natural advantage over their visual equivalents. If tactile and auditory representations of speech stimuli are more alike than are these and visual ones, then it is possible that the postlingually deaf may find it easier to attune to linguistically relevant cues when they are carried via a tactile percept. Likewise, the apparent similarity of auditory and tactile percepts may even allow the cognitive mechanisms involved in language processing to access and/or process speech information more readily when that information is presented via touch rather than via vision. Of course, these potential advantages for tactile prostheses also depend on the capacity of touch to deal with the rich patterns entailed in an adequate transform of speech [see Mahar and Mackenzie (1993) for a discussion of this issue].

8.2 Spatial and temporal information processing in hearing, touch, and vision

The present results also suggest one way in which auditory and tactile perceptual processes may differ from visual ones. Vision and touch were found to differ in terms of the style of information distribution which they process most efficiently. Experiments 4 and 5 demonstrated that touch processes temporally distributed information more efficiently than it does spatially distributed information. Results in experiments 4, 5, and 6 showed that the reverse is true for vision, with spatially distributed displays being processed more efficiently than temporally distributed ones. Further, data from experiments 5 and 6 suggest that visual processing is most efficient when both spatial and temporally distributed information are available together, as was the case in the spatiotemporal displays. This facilitatory effect was not found with tactile-spatiotemporal displays. These modality-specific differences in the efficiency with which spatially and temporally distributed information are processed by each modality held when either spatial or nonspatial characteristics of the display were compared. Thus, it seems that they were not artefacts of the particular type of information presented.

The present results do not show that the auditory, tactile, and visual modalities are unable to process displays where the information is distributed in a 'nonpreferred' form. Nor do they conflict with either Marks's (1987a, 1987b) 'unity of the senses' position or with his demonstration that the mechanisms underlying temporal pattern processing are similar in hearing, vision, and touch (Marks 1987a). What the present data do show is that these various senses are differentially effective in their use of any shared or similar temporal processing mechanisms.

This finding is relevant to recent discussion concerning the degree to which hearing and vision can be characterised as either spatial or temporal domains. Handel (1988a, 1988b) has argued that both auditory and visual events are inherently spatio-temporal, whereas Kubovy (1988) claims that the spatiality of auditory stimuli, and the temporality of visual ones, are largely absent from the perceptual experience of auditory and visual events, respectively.

Handel (1988a, 1988b) is of course correct in claiming that auditory and visual events have both spatial and temporal coordinates. Likewise, both modalities do take advantage of spatial and temporal processes when encoding stimuli. For example, vision temporally integrates information across saccades to form a representation of spatial stimuli whereas hearing relies on the spatial locus of stimulation along the
basilar membrane to encode sounds. However, this does not mean that hearing and vision treat these spatiotemporal events in the same way. Once a perceptual representation has been generated, speech sounds are most commonly identified via their temporally distributed aspects, whereas visual stimuli are primarily identified via spatially distributed cues.

In this light, the present results, taken with those of earlier studies, show that both hearing and touch can be characterised as temporal senses, with vision differing through its focus on spatially or spatiotemporally distributed aspects of perceptual representations. Of course, in the present experiments we used stimuli like those involved in transforms of speech and thus further research is required to confirm these effects across a wider range of tasks. For example, touch may be found to focus more strongly on spatially distributed information in form-discrimination tasks.

At the outset it was argued that the demonstration of similarities between hearing and touch may show those areas in which minimal recoding of the auditory signal is required before presentation to the skin. As the defining characteristics of spoken words, that is changes in amplitude and frequency, are typically distributed across time, the present results suggest that tactile displays of speech should preserve this temporally distributed nature of the speech signal. Conversely, it seems that a visual display of speech may require some recoding of these temporally distributed features into the spatially or spatiotemporally distributed order which vision prefers.

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