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Not fade away:
Tactile persistence and temporal integration

by

Karsten A. Loepelmann ©

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy.

Department of Psychology

Edmonton, Alberta

Fall, 1995

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ABSTRACT

Sensory substitution is the use of a sense modality as a replacement or adjunct for a modality that is impaired. The history of touch as an auxiliary sensory system for the visually impaired is reviewed, from systems like Braillle to devices like the OPTACON. The success of the latter systems is explained, in part, by the incorporation of fundamental research findings regarding general and specific discriminatory capabilities of the tactile sensory-perceptual system into their designs. A brief review is presented, providing justification of the use of the tactile sense as subsidiary information channel to vision.

An important goal of sensory substitution is the efficient transmission of stimulus information. One factor limiting rapid processing of stimulus information by the skin, though, is masking. This phenomenon arises when a masking stimulus presented in spatiotemporal contiguity with a target stimulus causes deterioration of the target. Evidence is reviewed which implicates temporal integration as the cause of masking, as opposed to an interruption-based hypothesis. Efforts to delineate the nature of temporal integration are reviewed. Two models based on an intrinsic persistence hypothesis are described. Intrinsic persistence is the notion that stimuli create a rapidly decaying neural trace, which may act to bridge the temporal gap between successive stimuli. The critical temporal variable in the storage model is the interval between stimuli, whereas the processing model relies on the difference in stimulus onsets between stimuli. These models contrast with the temporal correlation model (TCM), which suggests that a correlation of neural responses to stimuli is the basis for coding stimuli as integrated or segregated.

Four experiments were conducted. The first provides evidence that calls into question the efficacy of the storage model in accounting for the inverse duration effect. The second reveals that the processing model is better suited to accounting for temporal integration than the storage model, but also points out that there may exist a more parsimonious explanation. The third and fourth experiments illustrate how the TCM better accounts for performance in situations that the intrinsic persistence-based models cannot handle. Parallel research developments regarding temporal integration between vision and touch are discussed. Finally, implications of the findings for tactile reading are explored.

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INTRODUCTION

When the use of a sensory modality is severely diminished or lost, the amount of external, environmental information available is greatly reduced. For those with a significant hearing impairment, for example, a standard telephone is no longer a viable means of communication. For the visually impaired, newspapers, magazines, and books cannot provide information as they do for sighted people. Fortunately, there are ways of regaining access to information that would otherwise remain unavailable to those who are sensorially impaired.

Sensory substitution refers to the use of one of the remaining intact senses as a substitute or adjunct for an impaired modality. Employing another, ancillary sense commonly provides increased interaction with the environment in two ways. First, when vision—the primary modality employed for navigation through the immediate environment—is impaired, an auxiliary modality may make locomotion safer and easier. For example, the white cane used by the visually impaired provides feedback about the location of obstacles in the immediate environment directly through kinaesthetic feedback, and also via the localization of echoes produced by the tapping of the cane. Second, symbolic information such as printed text may be obtained from the environment via the substitute modality. For example, Braille employs a matrix of raised dots on paper to represent alphabetic letters, which may be "read" by the visually impaired. The focus of this paper is the temporal processing of symbolic information delivered to the tactile sense.

The selection of a modality to augment an impaired one must be made carefully. The tactile modality has been considered a feasible substitute for vision, for several reasons: the skin covers a spatially extended area, is highly innervated, and is capable of precise and varied discrimination (Lechelt, 1978). It should also be noted that both the visual and tactile senses are represented in the brain by a spatiotopic map, which provides direct location information. A description of the tactile sense is provided below. Fundamental issues regarding the interplay of instrumentation and psychological variables arising from tactile-based vision substitution systems are also discussed. The tactile sense may fulfill its potential as an information channel only if its capabilities are well understood, and if devices employing it as a substitute channel capitalize on its inherent, specific discriminatory capabilities.

The History of Touch as a Sensory Substitute

In 1824, Louis Braille invented a means of tactile "reading" using an alphabet of raised dots. Prior to the development of Braille, tactile books were printed with embossed letters. Reading these books proved an arduous task, as each letter had to be painstakingly traced to be identified. For example, to differentiate the letters *E* and *F*, the critical lower horizontal bar must be detected; distinguishing an *O* from a *Q* requires an even more careful examination. The Braille system replaced the cumbersome system of embossed letters, and proved to be much quicker and easier to use.

Since the development of such early methods, numerous other devices and systems have been constructed, utilizing widely disparate means of stimulation, from air puffs to electrical currents to mechanical stimulation. These cutaneous communication devices may be divided essentially into analogic systems and synthetic systems (Sherrick, 1975). Analogic systems use stimuli in the substitute modality that physically resemble the stimuli in the original modality. For example, the OPTACON, a reading aid used by the blind, provides the reader with a vibrating, digitized analogue of the printed letters on a page. Synthetic systems use novel representations of stimuli that differ from the form of the original stimuli. For example, although the patterns of Braille dots represent letters, they are not physically isomorphic with the printed Roman alphabet.

A similar dualism was proposed by Epstein (1985): transmodal perception and amodal information. "Transmodal percepts are functionally equivalent perceptual descriptions secured through application of different sense modalities" (p. 421), whereas amodal information is identical across modalities, and exhibits the same form of change over those different modalities. Thus transmodal percepts are equivalent to synthetic systems, and amodal information is the counterpart of analogic systems.

One of the earliest tactile sensory substitution devices was the Teletactor (Gault, 1927, cited in Sherrick, 1991), used by the hearing impaired. In one of its incarnations, this device transmitted the auditory vibrations produced by speech to the fingers of the hand. Filters divided the frequency range into five bands, and each band was presented to a finger and the thumb of one hand. Thus, the frequency components of speech were converted into a spatial representation; the temporal and intensity variations could be detected via the vibrations on the fingers. However, a considerable problem with the device was that it failed to compensate for the fact that the tactile modality is largely insensitive to frequencies above 1000 Hz, whereas it is not uncommon to have speech formants of 3000 Hz and above. The failure of the Teletactor serves to illustrate the problem of directly substituting one sense for another.

Another attempt at compensating for lost vision by presentation of stimulation to the skin was the development of the vibrotactile alphabet, "Vibratese," in the mid-1950s (Sherrick, 1991). Each letter of the alphabet (or a short word) was assigned a specific combination of one of five locations on the chest, one of three durations, and one of three intensities. Because one of the stimulus dimensions was duration, however, the theoretical upper limit of the rate of presentation was about 70 words per minute (wpm), although the best observer obtained a rate of only 38 wpm. An interesting problem with Vibratese was that observers commonly confused low intensity/long duration letters with high intensity/short duration letters; this problem has subsequently been attributed to the interaction of duration and perceived intensity due to temporal summation (see Verillo & Smith, 1976, cited in Sherrick & Craig, 1982). Although each stimulus had been carefully chosen within a dimension to be highly discriminable, when combined, their interactions created a "higher-order" level of confusion that greatly compromised the utility of the system. This particular failure clearly demonstrates the need for a thorough perceptual analysis of the entire stimulus complex, and an examination of how the enriched dynamics produced by an interaction of stimulus dimensions can create perceptual end results not predictable on the basis of variations in individual stimulus dimensions alone.

A considerable technological advancement in the development of specific tactile-based vision substitution devices was the Tactile Vision Substitution System or

TVSS (Bach-y-Rita, 1972). Instead of direct sensory substitution, the TVSS transduced the source stimuli. The observer sat in a modified dental chair, with an array of 400 solenoid vibrators contacting an area of 25 × 25 cm on his or her back. This bank of vibrators presented a real-time replica on the skin of an image acquired by a video camera manipulated by the observer. The tactile percepts were constructed serially, by repeated scans across the contours of an object with the camera. After a sufficient amount of practice, visually impaired subjects were able to identify objects such as a cup and a telephone from a group of 25 objects (Bach-y-Rita, 1983). Although modestly successful—at least in demonstrating that tactile vision substitution was indeed possible—the TVSS was ultimately considered impractical, due to its expense and lack of portability.

The problems inherent in the TVSS were in large part addressed by the subsequent development of the OPTACON (OPtical-to-TACtile CONverter), a small device that presents a digitized tactile image to the fingertip (Bliss, 1978). In typical use, a small digitizing camera connected to the device is moved across a line of printed text. An (approximately) isomorphic representation of the text on the page is presented to the user's fingertip via a 6 × 24 matrix of pins (measuring 1.1 × 2.7 cm) vibrating at 230 Hz. As a result, the letters move across the fingertip in a manner similar to "Times Square" electric signs, which present moving messages by illuminating a particular succession of light bulbs in a matrix. The OPTACON is used as a reading aid by visually impaired consumers. With extensive training, reading rates of 30 to 50 wpm can be achieved (Craig & Sherrick, 1982).

Unlike many of the other tactile sensory substitution systems listed above, much basic research was applied in the design and construction of the OPTACON. And, unlike the devices listed above, the OPTACON is—perhaps unsurprisingly—one of the most popular reading aids (Steele, Goodrich, Hennies, & McKinley, 1989). However, not all of the OPTACON's value lies in its employ by visually impaired users; the flexibility of the OPTACON in presenting stimuli affords an excellent opportunity to study the processing of tactile stimulus information applied to the skin. For example, Sherrick (1982) modified an OPTACON-type display to extend its spatial configuration, and has examined discriminatory capacities of larger skin surface areas such as the thigh and forearm.

The Structure and Function of the Skin

Due to its spatially extended nature, the skin is not only the most physically extensive of sense organs, it is also the largest organ in the adult human body, covering an area of 1.8 m^2 and weighing about 4 kg on average. The skin varies considerably in thickness, ranging from about 0.5 mm on the nose, to around 4.0 mm on the sole of the foot; its average thickness is approximately 1 to 2 mm. Skin tissue, depending on body site, also varies in other qualities such as hardness, or looseness; it may be hairy or non-hairy ("glabrous").

The skin is comprised of many layers. The epidermis consists of two layers: the corneum is the outermost layer of the skin, and is made up of dead skin cells from the underlying germinative layer. Below the epidermis lies the dermis (also known as the corium), formed of nutritive and connective tissues, and some muscles. Underneath the corium is the reticulated dermis, made of connective tissue housing hair follicles, sweat and sebacious glands, blood vessels, and elastic tissue which anchor it to the overlying structures. The structures believed to be tactile receptors exist at the epidermal-dermal boundary, or within the dermis.

When the skin is touched, biophysical properties of the skin cause it to interact with the kinetic energy applied to it. The skin is elastic: upon being deformed by contact, it absorbs some of the energy, which is used to return the skin to its normal resting state. The skin is also viscoelastic, transmitting some of the contact energy along itself (Cholewiak & Collins, 1991). Tactile stimuli are propagated along the surface of the skin via a damped traveling wave, which is produced by shear and compression waves in the deeper substrates (von Békésy, 1967). It has been found on skin overlying muscles that the damping function attenuating the shearing force adheres to the inverse-square law (Sherrick & Cholewiak, 1986). The differences in morphology of the skin at various body sites influence the transmission of the traveling wave, thus differentially affecting the transduction of the energy by the receptors at those locations (e.g., see Johnson & Phillips, 1981 for a model of tissue mechanics).

End organ structure

There are numerous cutaneous end organs—named after their discoverers—distributed throughout the dermal layer of the skin; these structures are believed to be tactile receptors. The density of innervation and distribution of the different structure types varies over body location. Thus, the skin is not uniformly sensitive over its surface to all forms of stimulation. There are "sensory spots," which exhibit a punctate sensitivity to certain stimuli (e.g., cold). Also, certain body locations, due to a high degree of innervation, are highly sensitive to stimuli (e.g., the fingertips).

Free nerve endings are the most common neural termination in the skin. In hairy skin, multiple fibres form cylindrical structures around hair follicles, producing what are often called "basket endings," due to their woven morphology. Merkel's disks are situated near hairs; the afferent fibres innervating these structures branch and connect to multiple end organs. Ruffini cylinders, spindle-shaped capsules about 0.5-2.0 mm long, are also found in hairy skin. The nerve fibre leading from a Ruffini ending innervates only one end organ.

In glabrous skin, encapsulated structures are commonly found. Meissner corpuscles are found in greatest quantity in the papillary ridges of the fingertips, and are connected to the surrounding tissue by connective tissue. Each corpuscle may have up to nine nerves, each of which may innervate multiple corpuscles. The effect of this coexistent neural divergence and convergence on the neural coding of stimuli is not well understood. Merkel cell-neurite complexes (MD) are unusual in that epithelial cells seem to transduce mechanical stimulation and appear to synapse with the afferent fibre. MDs were once thought to be encapsulated endings called Merkel's disks (Sherrick & Cholewiak, 1986).

Pacinian corpuscles (PCs) are the most-studied end organ because of their size (about 1 mm long and 0.6 mm thick), which allows for easy dissection. PCs are located deeper than the structures described above: about 2-3 mm from the skin surface. They have a multi-layered lamellate encapsulating a nerve ending. Each corpuscle has a single, dedicated line to the brain. Research has revealed that the PC is sensitive to a pressure gradient that produces a burst of firing that quickly subsides, even with continued stimulation. Loewenstein and Skalak (1971, cited in Goldstein, 1984) were able to remove the laminar surround from the PC, and found that when pressure was applied directly to the underlying nerve fibre, it would continue to respond as long as the pressure continued. Thus it would seem that the mechanical properties of the corpuscle itself play a role in tuning the organ to specific types of stimuli.

Function

The relation between receptors and sensory experience has been a subject of investigation for over a hundred years. In the 1890s, Max von Frey published a number of papers on sensory coding, outlining his specificity theory. Von Frey proposed an isomorphic correspondence between (assumed) receptors and primary sensations. Specifically, when stimulated, Ruffini endings were thought to produce the sensation of warmth; Krause end bulbs, cold; Meissner corpuscles, touch; and free nerve endings, pain. Mappings of the skin, though, have revealed little correlation between the type of sensory spot sensitive to a particular stimulus type and the cutaneous end organ at that site (Goldstein, 1984). The issue of receptor-sensation correspondence is more complex than it initially appeared.

A tactile receptor may be defined as a neuron capable of transducing a specific form of mechanical energy into an electrical energy code. Classification by structure aids in establishing whether a given end organ is a receptor (Cholewiak & Collins, 1991). That is, the end organ producing a specific neural response to a tactile stimulus must be determined. However, current single-unit recording techniques only allow the relation between a given stimulus and a particular fibre to be established. It is nearly impossible to isolate the suspected receptor structure for histological examination and also measure the electrical response of the connected fibre for two important reasons. First, because the skin transmits the force of a touch across its surface, it is possible that receptors distant from the site of stimulation may be triggered. Second, upon dissection of the skin constituting the receptive field associated with an isolated fibre, numerous receptors of various types have been found, making it impossible to conclude which one was responding.

Classification by function provides a means of relating the neural responses of an afferent fibre with the sensations evoked by a stimulus. Microneurography is the technique of recording from a single unit in an awake human by inserting a microelectrode through the skin into the fibre. This method allows neural responses to be related to reportable sensations. Vallbo and Johansson (1978) provided a functional classification of cutaneous afferent fibres, based on single-unit recordings in humans. Four functionally separate tactile sensory units were found.

One type of fibre responded only to an onset, offset, or significant change in the stimulus (variously a moving coil stimulator, glass rod, or von Frey hair), and was thus deemed the RA or "rapidly adapting" unit. The receptive fields of RAs are small, with distinct borders, and possess multiple sensitivity maxima, which likely indicates the existence of several end organs within a single receptive field. Vallbo and Johansson

(1978) suggested that Meissner's corpuscles, with their relatively high degree of neural interconnectedness, are responsible for these multiple points of sensitivity. Thus, RA fibres probably innervate Meissner's corpuscles.

The PC fibre also exhibited a response to static stimulation. It was found to have large receptive fields with indistinct borders; within each receptive field was located a single sensitivity maximum. PC units are sensitive to high frequency vibration. It has been shown that these fibres are connected to PCs (Vallbo & Johansson, 1978).

Units exhibiting a static response, having small receptive fields with distinct borders and several sensitivity maxima were designated SA I (slowly adapting type I). The receptive fields of SA I fibres are smaller than any other unit. Because the receptive field organization of SA I fibres is similar to that of RAs, Vallbo and Johansson (1978) proposed that the very interconnected Merkel cell neurite complexes are innervated by SA I fibres.

Another type of slowly adapting unit was found: SA II fibres produce a static response, have large receptive fields with a single sensitivity maximum and indistinct borders. These units are only found in humans, and demonstrate a high sensitivity to stretching of the skin; they are believed to be connected to Ruffini endings (Vallbo & Johansson, 1978).

Overall, Vallbo and Johansson (1978) suggested that tactile sensitivity is dependent upon the receptive field size of sensory units, as well as the density of distribution of these units. A direct relationship was found between the size of receptive fields and the density of neurons with small receptive fields; further, more distal areas (e.g., the fingertip) exhibited the greatest density of tactile sensory units. It was proposed that the high sensitivity of the RA and SA I units would make them well suited to fine spatial analysis.

Johnson and Lamb (1981) moved Braille-like embossed-dot patterns across the fingertips of monkeys and recorded the responses from SA, RA, and PC units. By reconstructing the response relative to the centre of the particular unit's receptive field, it was found that the SA channel is indeed better at detecting higher spatial frequencies (has a greater spatial bandwidth) than the RA or PC units. Freeman and Johnson (1982, cited in Loomis & Lederman, 1986) investigated the temporal response of SA, RA, and PC units in monkeys and found that each acted as a bandpass filter centred around a particular frequency of stimulation. SA fibres passed the lowest central frequency, around 20 Hz; RA around 40 Hz; whereas PCs are centred the highest, around 250 Hz. These differences in temporal sensitivity between fibre types are likely responsible for the dual nature of mechanical sensibility (i.e., flutter-vibration) obtained by Mountcastle, Talbot, Darian-Smith, and Kornhuber (1967).

Johnson and Hsiao (1992), upon reviewing the psychophysical and neurophysiological evidence, posited hypotheses for the function of each afferent system. The primary spatial system is the SA I system, which is responsible for tactual form and texture perception, via both direct and indirect stimulation. The PC system handles the perception of events that are manifested through high-frequency vibrations (e.g., as in tool use). The RA system, having poorer resolution than the SA I system but a greater sensitivity to vibration, detects movement between the skin and an object's surface, as well as some surface structure and form not handled by the SA I system.

Structure Versus Function

Although there seems to be general agreement regarding the nature of the relation between receptor structure and function, there are occasions of this assumption being treated as fact. Loomis and Lederman (1986) avoided any mention of receptors, focusing instead on the functional properties of the afferent fibres. Sherrick and Craig (1982) cautioned against attributing any functional characteristic to a single receptor type, as a given sensation may be the result of a multiplicity of stimulated receptor types. Sherrick and Cholewiak (1986) stated that there is "general agreement" on the cutaneous end organs believed to be receptors. They list and describe the end organs, but classify receptor function separately. Importantly, they do not associate specific afferent fibres with any cutaneous structures. Cholewiak and Collins (1991) avoid calling any end organ a receptor; they also note the difficulty of classifying sensations by structure. Vallbo and Johansson (1978) suggest the most likely structural candidates for each fibre type, but also caution against assuming these relations to be fact. On the other hand, Kandel and Jessell (1991) and Martin and Jessell (1991) not only label the cutaneous end organs as receptors, but also equate each structure with a particular sensation. Johnson and Hsiao (1992) also list the end organ-fibre associations as fact. It is almost certain that the cutaneous end organs produce neural responses, which are centrally interpreted as sensations. However, the exact relationships between the cutaneous structures and their function have yet to be conclusively established (Cholewiak & Collins, 1991).

Cortical Organization

All of the above afferent fibres (and, presumably, the associated end organs/receptors) are dorsal root ganglion neurons. These neurons transduce physical energy and transmit the encoded information to the central nervous system (Martin & Jessell, 1991). Vallbo and Johansson (1978) noted that the mechanoreceptors in the glabrous skin of primates seem to be innervated by large-diameter myelinated nerve fibres (designated Aα). Martin and Jessell (1991), however, reported cutaneous and subcutaneous mechanoreceptors as small myelinated fibres (Aβ), and described muscle and skeletal mechanoreceptors as Aα.

The central branches of the dorsal root ganglia ascend in the dorsal columns. In the dorsal column nuclei, these neurons synapse with second-order cells, the axons of which cross the midline in the medulla and ascend (contralaterally) through the brain stem, comprising the medial lemniscus. These neurons then synapse with third-order cells in the ventral posterior medial and ventral posterior lateral nuclei of the thalamus. From the thalamus, the neurons project to the primary somatic sensory cortex (S-I) in the postcentral gyrus of the parietal lobe (Kandel & Jessell, 1991).

The S-I is divided into four areas: 1, 2, 3a, and 3b; each of these areas projects to S-II, the secondary somatic sensory cortex, which is also partly innervated by thalamic neurons. Separate sensory homunculi (or somatosensory maps) can be found in each of the areas of S-I; as well, S-II embodies its own homunculus. Areas 3a and 3b receive the most thalamic input, and project to areas 1 and 2, which receive far less thalamic input. Cells in areas 3a and 3b are triggered by simple punctate stimuli, whereas there exist neurons in areas 1 and 2 that respond to more complex input (e.g., there are motion-sensitive, direction-sensitive, and orientation-sensitive neurons). The receptive fields of neurons in areas 1 and 2 are also larger than those in 3a and 3b, and also exhibit more convergence and integrative processes. Thus, it is apparent that areas 1 and 2 comprise a later stage of cortical processing (Sakata & Iwamura, 1978).

Considerations for a Sensory Substitution System

Bach-y-Rita (1972) noted that, "So long as the display presents the information reliably, the brain can apparently be trained to use the information as it uses the information from any of the intact sensory systems," (p. 32). However, what constitutes "reliably" is not immediately apparent. Can stimulation varying in time and space such that it is suitable for vision be similarly processed by the skin? That is, how direct can the substitution of touch for vision be? To answer these questions, the relevant research with respect to the OPTACON is reviewed.

There are many factors involved in the decision of which body site to employ for sensory substitution. It is no coincidence that many of the sensory substitution devices described above employed the hand one way or another. Indeed, the fingertips are the most sensitive, have a small two-point threshold, are convenient to use, and this sensory surface is reasonably well understood—both physiologically and psychophysically (Sherrick, 1972).

The National Research Council (1986) noted that the stimulation produced by the OPTACON is poorly matched with the optimal underlying receptor mechanism: the 230 Hz vibration of the tactile display triggers only the rapidly adapting (RA) and Pacinian corpuscle (PC) afferent channels; it fails to activate the highest-resolution slowly adapting (SA) channel (Gardner & Palmer, 1989a). It should be noted, though, that activating the SA channel would increase the spatial bandwidth, but would also decrease the rate of information transmission, because of the difficulty involved in activating the SA channel with sufficient rapidity to allow efficient reading.

The density of pins on the OPTACON's display was described as being well below maximum perceptual acuity by the NRC (1986). This conclusion was based on the fact that receptive fields of RA fibres span an average of 3.4 rows of the tactile display; receptive fields of PCs span an average of 5.4 rows (Gardner & Palmer, 1989a). Adjacent rows on the OPTACON's tactile display are separated by 1.2 mm; columns by 2.5 mm. However, the sharpening effects of mechanical and neural mechanisms in the skin are well known (e.g., see von Békésy, 1959). Indeed, further research indicated that due to overlapping receptive fields, single-row gaps on the OPTACON can be reliably detected, and that two-point resolution and discrimination of single bars is possible (Gardner & Palmer, 1990). Whether or not an increased-density vibrotactile display would aid in letter identification, although unlikely, is yet to be determined.

Recommendations were drafted by the NRC (1986) for the development of future sensory substitution systems. Among the proposals, it was suggested that patterns presented to the skin should be isomorphic with the visual representation of the stimulus, as with the OPTACON. However, Craig (1974, cited in Craig & Sherrick, 1982) found that, after training to a criterion, subjects were able to learn and recognize arbitrary cutaneous patterns associated with letters as well as cutaneous patterns isomorphic with Roman alphabetic characters. Craig (1974) concluded that a pictorial representation is not necessary for letter-recognition tasks. That is, the form of the stimulation on the skin need not be equivalent to the form of the visual stimulus. It must not be overlooked, though, that the OPTACON was designed to reproduce text isomorphically to allow users the greatest access to otherwise unavailable printed materials.

Attempting to duplicate findings that visual reading is accelerated by increasing the field of view to include more letters in the tactile domain, Hill (1974) presented vibrotactile words moving across two adjacent fingertips. The result, however, was that performance declined, indicating that spatial integration between fingers may not be possible. Further experiments showed that an expanded display on a single fingertip did not improve performance from baseline (Hill, 1974). Thus, it is apparent that the fingertips extract information from only a small area; designing larger displays does not provide a perceptual advantage.

The above review serves to illustrate the importance of basic research to a fundamental understanding of the underlying sensory neurophysiological basis of the sense of touch, and the consequences of these limiting factors to tactile perception. Applied research into sensory substitution, too, is needed (Sonnier, 1985; Sonnier & Riesen, 1985). It is clear that the skin cannot process information in the same way as the retina. Indeed, the brain is not so plastic as to accommodate tactile information isomorphic with vision (Lechelt, 1984). Thus, it is crucial that we learn the skin's language by delineating its discriminatory capacities and then, from a human factors perspective, develop a prosthetic system that best accommodates these sensory and perceptual capabilities (Lechelt, 1986).

The Language of the Skin

Vision and touch differ fundamentally and significantly in how they receive and process stimulus information. Essentially, vision is a primarily parallel system, whereas the skin processes stimuli more serially (Bach-y-Rita, 1983). One may attempt to compensate for this difference by using time-division multiplexing, in which a large or complex image is broken down into several distinct components, each of which is presented in succession to the observers' fingertip via an OPTACON display. The observer then synthesizes the whole from its constituent parts. This method takes advantage of the fact that the skin is better suited to process stimuli presented in a serial manner. It was found that synthesizing an image from components having "high goodness" in their structure (e.g., shapes composed of intact, familiar geometric forms) led to fewer errors than constructing a pattern based on a number of randomly extracted parts or line segments; a similar finding was obtained for visual stimuli (Bach-y-Rita & Hughes, 1985). A further experiment examined the tactile equivalent of the kinetic depth effect, which is the perception of rotation and apprehension of an object's three-dimensional structure, based on the transformation of two-dimensional patterns. For example, in the visual domain, the kinetic depth effect is obtained by projecting the shadow of a rotating wire coil onto a screen. It was found that this effect could also be produced on the skin by a two-dimensional tactile pattern (Bach-y-Rita & Hughes, 1985).

These studies suggest that, despite the differences in the processing of stimuli between vision and touch, there exist similarities in the form and function of internal representations across modalities. If this is indeed the case, any commonalities in the functional architecture may exist at more central, as opposed to more peripheral, levels. It is crucial to a complete understanding of the perceptual system that the extent of these spatiotemporal similarities are fully delineated.

Because one of the goals of sensory substitution is the efficient (i.e., rapid and accurate) transmission of information, outlining the processing of tactile stimuli in time is important. The largely serial nature of the tactile system creates a bottleneck in the flow of information. It may prove useful to examine the parallels in the temporal domain between the modalities of vision and touch. The next section reviews the nature of the temporal aspect of the processing of tactile patterns.

Tactile Persistence

It has been reliably found in pattern detection and recognition tasks that if two vibrotactile patterns are presented in sufficiently close spatiotemporal contiguity, one will interfere with the other (e.g., see Craig, 1983a). Specifically, temporal masking is the usually deleterious effect on a target pattern produced by a masking pattern preceding it (forward masking) or following it (backward masking). Temporal masking places a limit on the rate of information that the skin is able to process: if patterns are presented such that masking occurs, the information contained in the patterns will become degraded, or not even perceptible. The phenomenon of masking, however, may also be used as a tool to reveal the mechanisms underlying the processing of tactile information.

Using a masking paradigm, similarities between tactile and visual temporal processing have been obtained. Craig (1978), employing a tactile recognition-masking paradigm in which letters served as targets, found more backward than forward masking—a result that parallels visual masking studies. There are two competing—yet not necessarily mutually exclusive—explanations of these results in the visual domain: integration and interruption. Integration occurs when a masker interferes with the target by adding its energy to that of the target; as a result, it is difficult to separate the two patterns out of the composite representation. Interruption is produced when the masker interrupts the processing of a target pattern; thus, the representation of the target is incomplete. In the visual domain, if integration is responsible for masking, it is believed that both forward and backward masking should be equal. Alternatively, if interruption is the cause of masking, it has been hypothesized that no forward masking should occur. Thus, Craig (1978) attributed his tactile masking results to a confluence of integration and interruption.

In a further experiment employing conditions similar to the one above, Craig (1978) measured the amount of detection masking. In this experiment, however, more forward than backward masking was produced. This perhaps anomalous result was ascribed to the qualitative differences existing between the recognition and detection tasks. The detection task simply requires the observer to make a yes/no decision about rudimentary pulse stimuli, whereas the recognition task, employing complex spatial forms such as alphanumeric characters, requires higher-level cognitive processes to identify the stimulus. In a recognition task, the chances of the structural components of the masker and the target interacting are much greater than in a detection task.

The effects of energy and pattern maskers on an identification task were further examined in an attempt to determine the relative effects of integration and interruption (Craig, 1982a). In a letter recognition task, a greater effect was produced by a pattern masker (e.g., horizontal, vertical, or curved line segments) than by an energy masker (e.g., all tactile stimulators in the array turned on at once), and there was more backward than forward masking; these findings are in agreement with results in the visual domain. In addition, there was a greater difference between backward and forward masking for the pattern masker than for the energy masker. On the basis of the above findings, Craig (1982a) further elaborated a two-factor theory of vibrotactile pattern masking: an energy masker is believed to interfere with a temporal integration process by reducing the signal-to-noise (i.e., target-to-masker) ratio, whereas a pattern masker is thought to disrupt the processing of features of the target.

Further research (Evans & Craig, 1986) supported the role of temporal integration over that of an interruption process in vibrotactile backward masking. An integration-based model of masking was developed by Craig (1984). This model is based on the premise that the presentation of a vibratory stimulus "yields an internal representation that persists in a fashion similar to the persistence of a visual pattern in iconic memory" (Craig & Evans, 1987, p. 316). Thus, when stimulus patterns are presented in temporal contiguity such that one pattern persists and becomes integrated with another, the result is masking of one pattern by another. However, there remained the question of just how persistence behaved over time.

There have been several attempts to describe the nature of the tactile persistence function. These accounts have closely followed theoretical developments and research in the area of visual persistence. Two past conceptions of tactile persistence, the storage model and the processing model, are described below, followed by an account of the phenomenon presently under consideration, the temporal correlation model.

The Storage Hypothesis

The notion of persistence was developed as a result of early research in iconic memory. Visual information in a stimulus may be available for brief period of time after stimulus offset, due to the mediating influence of a kind of short-term sensory store, generally referred to as "iconic memory" (Coltheart, 1980). Because information in the stimuli persisted even after the offset of the stimulus, it was inferred that a representation of the stimulus continued to be visible ("visible persistence"), and visual information could still be extracted from iconic memory ("informational persistence").

According to the storage hypothesis, a representation of the stimulus is constructed at stimulus onset and begins to discharge only when the inducing physical stimulus is removed. If another stimulus is presented before the representation of the first has degenerated sufficiently, the representations become integrated and perceived as temporally overlapping. This conception of the persistence function relied greatly on the amount of time between the offset of a leading stimulus and the onset of a trailing stimulus: the inter-stimulus interval (ISI).

Research into the tactile equivalent of the storage model suggested that integration of stimuli increased as the ISI between them was reduced (Gescheider, 1974; Rosner, 1961). Although these early tactile results agreed with those obtained in the visual domain, evidence soon appeared that indicated that both the visual and tactile persistence functions could not be characterized by ISI alone (e.g., Di Lollo, 1980; Craig, 1982b), requiring a reinterpretation of the nature of the function.

The Processing Hypothesis

It was found that visible persistence did not behave like the traditional characterization of a sensory store that depends on the ISI between stimuli (Di Lollo, 1980; Craig, 1982b). The storage hypothesis was called into question by the inverse duration effect: All other things being equal, the longer the duration of the leading stimulus, the shorter its persistence after stimulus offset (Coltheart, 1980). In this situation, the storage hypothesis predicts that stimulus duration should have no effect on persistence. Because of this shortfall of the storage hypothesis, an alternative account of persistence was proposed by Di Lollo (1980): According to the processing hypothesis, persistence is produced when the neural processes in the visual system caused by an inducing physical stimulus outlast that stimulus. Processing is comprised of sensory (e.g., encoding) and perceptual (e.g., identification) phases; visible persistence is a function of the former phase. Assuming that the rate of decay of persistence is a constant and that decomposition begins at stimulus onset, persistence is briefer for longer duration stimuli because by the time of stimulus offset, the sensory phase of processing has become significantly diminished. Thus, the critical variable for the persistence function must be the time difference between the onsets of the stimuli (stimulus onset asynchrony, or SOA). The inverse duration effect is accounted for by the processing hypothesis: it is induced by either a longer duration of the leading stimulus, or a longer ISI (both of which comprise the SOA—thus SOA better explains the phenomenon). Temporal integration can be seen as occurring when the persistence of the leading stimulus overlaps with the processing of the trailing stimulus.

Research for the tactile equivalent of the processing hypothesis proposed in the visual system provided favourable results. A possible mechanism for masking is the integration of target and masker if the two are presented in sufficient spatiotemporal contiguity. In an effort to better delineate the effects of the temporal integration function on masking, Craig (1982b) spatially split letters in half and varied the time between the onset of presentation (SOA) of each letter-half. In order for the observer to correctly identify the letter, it is assumed that the two halves must be integrated to produce a complete representation. If temporal integration does not take place (e.g., because the SOA is too great), the letter cannot be identified. It was found that complete temporal integration was produced when the SOA was less than 10 ms, and declined to asymptote between 50 and 100 ms. In another series of experiments (Craig, 1983b), various patterns including letters served as targets, and were presented in conjunction with either energy or pattern maskers; observers were required to discriminate between the target and the masker. The results indicated that as SOA decreased, the target and masker became integrated. The findings of the above research were taken as evidence that the representation of the contour of tactile patterns is formed and begins to decay immediately (i.e., at pattern onset), thus implicating SOA as the critical variable in temporal integration.

Further research showed that integration was responsible for vibrotactile backward masking at short SOAs (Evans & Craig, 1986). At longer SOAs (i.e., greater than 100 ms), the results are congruent with findings in the visual domain that maskers interfere with the extraction of higher-order relational information in the target (Di Lollo, 1980). To further explore this effect, Craig and Evans (1987) presented observers with target patterns consisting of line segments, and a forward masker. At long SOAs, it was found that the observers overestimated the number of component line segments in the target. The results were taken as evidence that an isomorphic representation of the features of a vibrotactile stimulus is constructed, and lasts for up to 1200 ms. This mechanism was used to account for forward masking: some features of the masker may persist and become integrated with those of the target, making identification of the target more difficult. Evans (1987) elaborated on the above experiment by presenting targets and backward maskers that, if integrated, would produce patterns that matched other possible targets. It was found that at shorter SOAs the observers did indeed erroneously identify the targets as the composites; at longer SOAs, the errors decreased. It was concluded that persistence is dependent upon SOA.

The Temporal Correlation Model

Both of the above hypotheses are dependent upon the notion of intrinsic persistence, which holds that a stimulus remains phenomenally available for a period of time after the offset of the inducing physical stimulus. The duration of this persistence is believed to determine whether two spatiotemporally contiguous stimuli become integrated or not. Persistence can thus be viewed as bridging the temporal gap between two successive, physically discrete stimuli, making them perceptually overlapping, if not simultaneous. To estimate the persistence function, the gap between two stimuli is increased until the stimuli are no longer integrated, at which point the persistence is said to have decayed. Thus, the persistence is not directly observed; rather, its existence is inferred from the temporal integration of successive stimuli. Both the storage and processing hypotheses depend on the idea of intrinsic persistence to account for the temporal integration of successive stimuli.

However, intrinsic persistence cannot account for some phenomena. For example, although it is apparent how two brief stimuli can become integrated due to the mediating influence of persistence, it is not clear how a succession of stimuli that comprise a moving pattern can be perceived without producing trails of motion smear. Also, an intrinsic persistence account posits that the duration of the trailing stimulus should have little effect on integration (something that is examined empirically below). Another criticism is that persistence is not perceived directly; it is only inferred from the temporal integration function. Because of these problems, the relevance of intrinsic persistence concept comes into question.

Recently, a more comprehensive model of visual temporal integration was proposed: the temporal correlation model (Di Lollo, Hogben, & Dixon, 1994; Dixon & Di Lollo, 1994). This model is significant in that the role of intrinsic persistence is downplayed. The temporal correlation model (TCM) is dependent upon the spatiotemporal contingencies of a stream of stimuli in determining how to code the stimuli. Although the spatial component of stimulus information is neglected, the TCM provides a good account of the temporal coding of stimuli. Whether stimuli are perceived as coextensive or disjoint depends on a temporal coding process that correlates neural activity produced by the stimuli over time—this neural activity is delayed in time and longer than the inducing stimulus. (In the visual system, this neural activity is referred to as "visual responses"; "tactile responses" are taken as the tactile counterpart.) These correlations are based on regular samples taken of the neural activity; a high correlation results from a high degree of similarity of neural activity over time. It is assumed that neural activity produced by two stimuli will be highly correlated if the inducing physical stimuli are similar—that is, being presented for similar durations, for example. If there is a sufficiently high correlation in neural activity, the stimuli are coded as coextensive and may be perceived as temporally overlapping.

The correlational mechanism need not wait until the neural activity has returned to baseline to be initiated; to facilitate timely calculation, it is hypothesized that a running average of values taken from samples of neural activity is used to estimate the correlation. Thus, after just a few samples, the correlation can be estimated. Keeping a running average is like having a sliding window on the neural activity. The estimates of the correlation obtained in this manner can vary, depending on the sampling rate and the width of the sliding window (i.e., the speed with which the running totals decay). The probability of integration increases with the estimated correlation; stimuli will be perceived as integrated when the estimated correlation exceeds some criterion.

The two sets of stimuli in Figure 1 provide an illustration of how differences in temporal parameters may affect the neural responses on which the correlations are based. The correlation is drawn from samples of the neural responses; areas representing high correlations in the Figure are shaded. Although the physical stimuli in Figure 1a do not overlap temporally, the neural responses exhibit a strong correlation. In contrast, placing a gap between the stimuli as in Figure 1b (effectively increasing both the ISI and the SOA) produces a lower correlation. As a result, the stimuli in Figure 1a are more likely to be coded as coextensive; the stimuli in Figure 1b are more likely to be coded as disjoint. Note that the shape of the functions of the neural responses are assumed to be that of the impulse response function (Dixon & Di Lollo, 1994).

The effect of manipulating the duration of stimuli is shown in Figure 2. The physical stimuli in Figure 2a have identical durations, whereas the duration of the leading stimulus in Figure 2b is much greater than the trailing stimulus. Based on correlations of the neural responses, the stimuli in Figure 2a are more likely to be coded as coextensive than the stimuli in Figure 2b. Note that this manipulation also increases the SOA.

Figure 3b illustrates that an increase in the duration of the trailing stimulus produces a lower correlation than the two stimuli of equal duration in Figure 3a. If the durations of two stimuli are too disparate, they are less likely to be coded as coextensive. Note that manipulating the trailing stimulus duration does not affect the ISI or the SOA, thus allowing predictions to be made based on the TCM in conditions that are not accounted for by either the storage or processing models.

Although there is much evidence in favour of the tactile version of the processing hypothesis (e.g., see Craig, 1983a), some studies have found that a complete account of performance cannot be based on just SOA. Employing moving bars as stimuli, Loepelmann and Lechelt (1992) noted that SOA alone could not describe motion direction discriminations; the results indicated that stimulus duration also influenced performance. Differences in ISI were also found to have an effect on temporal gap detections, again indicating that more predictive power was needed than was obtained by an SOA-based model (Loepelmann & Lechelt, 1993). This paper is intended to investigate the feasibility of creating a successor to the processing hypothesis—one based on temporal correlations among stimuli. Obtaining empirical support for this model would serve two purposes. First, a better understanding of the nature of the tactile temporal integration function would be gained. This finding would have implications for users of tactile sensory substitution devices, as it may provide for a more efficient and rapid means of stimulus information delivery, and thereby give the visually impaired better access to printed or digitally stored information. Second, obtaining evidence of a commonality in the temporal processing of information between the visual and tactile senses may aid in uncovering the neural basis of this mechanism.

Conclusion

The skin cannot be treated as the tactile equivalent of the retina. It is apparent that the extent to which the tactile sense and vision have similar information processing mechanisms must be determined. Indeed, the discovery of such commonalities—or differences—have broad theoretical and applied implications. If aspects of tactile information processing (e.g., persistence) differ significantly from the visual modality, compensations must be made when using touch to substitute for vision. On the other hand, if further similarities between these two senses are found, it would go a long way to reinforce the hope that touch can be employed as a viable substitute for vision (in addition to providing much insight into cross-modal perceptual phenomena).

The extent to which vision and touch differ in information processing is crucial to the design of future devices for sensory substitution or augmentation. If the eye and the skin are significantly different in this respect, it may be that the application of Sherrick's (1975) analogic systems is not feasible, and synthetic systems should be favoured.

EXPERIMENT 1

This experiment is designed to establish the efficacy of the storage model of tactile persistence using a form-part integration task. Although the observers' task is ostensibly that of tactile spatial gap detection, the specific task analyzed here requires that the stimuli are presented in sufficient temporal contiguity such that a judgment regarding the spatial separation between the stimuli can be made. Thus, if the stimuli are separated by an amount of time that precludes temporal integration, performance should be at chance levels—50% correct. That is, observers should not reliably be able to determine whether or not a spatial gap exists between the temporally separated, non-integrated stimuli. According to the storage model, the representation of the stimulus begins to discharge at its offset, so the critical temporal variable governing temporal integration is the ISI between successive stimuli.

This experiment is intended, in part, as a replication of earlier work (e.g., by Craig, 1982b), for the purpose of establishing a basis of comparison for the various competing models.

Method

Subjects

Four sighted volunteers, Department of Psychology students, served as observers in Experiment 1: two males and two females. The two male observers had participated in previous sensory-perceptual experiments employing the OPTACON device; the two female observers had no prior experience with the apparatus. None of the observers had used the OPTACON as a tactile reader. These observers participated in Experiments 1, 2, and 3; however, only the two male observers also participated in Experiment 4.

Apparatus

The apparatus consisted of an OPTACON (OPtical-to-TActile CONverter) tactile display, interfaced with an IBM PC XT microcomputer (Loepelmann & Lechelt, 1991). Each of the 144 piezoelectric bimorph reeds or "pins" on the OPTACON's tactile display (6 column × 24 row array, measuring 1.1 × 2.7 cm) vibrates at 238 Hz, and is under computer control. The display is designed to contact the distal pad of the observer's left index finger. Observers used their right hands to initiate trials and make responses by pressing one of five pushbuttons on a switchbox.

Stimuli

For all experiments, the stimuli consisted of a pair of horizontal "bars," presented either simultaneously or in succession. A bar is defined as two adjacent computer-activated rows of stimulators on the tactile display. There was a spatial gap of either zero or two rows of inactive stimulators between the pair of bars. The bars were presented on the uppermost 18 rows of stimulators of the display, ensuring that the stimuli contacted the more uniformly sensitive tip of the finger. To preclude the observers' using the absolute location of the pair of bars as a basis for their response, the absolute location of the bars was selected randomly, and the bar that was presented second appeared either distal or proximal to the first bar; these choices were selected with equal probability.

To obtain a suitable range of differential response accuracy, certain temporal parameters of the stimuli were manipulated. Specifically, the durations of presentation of the leading stimulus were 5, 10, 15, or 20 ms, and the ISIs between stimuli were 0, 5, 10, 50, 100, or 150 ms. The duration of the trailing stimulus was held constant at 15 ms.

Procedure

Each subject sat in front of the OPTACON with the distal pad of his or her left index finger resting on the tactile display. The amplitude of pin vibration was kept at the same level for all observers and all experiments. Trials were presented using a yes/no procedure, and were self-paced (i.e., there were no time restrictions on the duration of experimental sessions). Half of the trials contained a spatial gap of two rows; in the other half, no spatial gap was presented. These "zero-gap" catch-trials were necessary for data analysis using the $P(C)_{max}$ procedure (see below). Observers were instructed to indicate whether or not they perceived a spatial gap between the pair of bars. Responses were made by pressing one of two buttons (*gap detected* or *no gap detected*) on the switchbox; trial-by-trial feedback was given.

Design

This experiment was designed as a 2 (gap size) × 4 (duration) × 6 (ISI) factorial experiment with 48 separate conditions. Each observer ran through the experiment such that 100 trials per data point were collected in each condition; the experiment was divided into 50 sets of 96 trials each. Observers alternated between Experiments in which they took part every five sets; each set took approximately five minutes to complete.

Hypotheses

By examining the percentage of correct responses in each experimental condition, the amount of temporal integration can be assessed (and thus the tactile persistence function may be inferred). The storage model posits that the representation is fully "charged" shortly after onset and begins to discharge at stimulus offset. Thus, gap detection performance should decrease with increasing ISI: As the bars become greatly separated in time, the representation will deteriorate—precluding integration—and gap detection performance will approach chance levels at asymptote. Note that comparisons are made among ISIs within each stimulus duration value.

However, in accord with previous research (e.g., Craig, 1982b) but counter to the storage hypothesis, it is expected that gap detection performance will decrease as the leading stimulus duration increases: This phenomenon is known as the inverse duration effect. The finding that integration declines as duration increases—even if ISI is held constant—would be inconsistent with the storage model, and indicative that temporal integration is governed not by ISI, but rather by SOA (Di Lollo, 1980).

Results and Discussion

Observers' reports of whether or not a spatial gap was presented (i.e., proportion correct gap detection) are used as the dependent variable in all Experiments. The yes/no procedure described above can lead to a possible observer bias component in the responses. To compensate for the effects of this bias, the proportion correct responses are normalized using the $P(C)_{max}$ procedure (McFadden, 1970; Swets, 1964). After the responses are normalized, an analysis of variance (ANOVA) are performed.

In the $P(C)_{max}$ procedure, the probability of making a HIT (proportion of correct gap detection trials) and the probability of getting a FALSE ALARM (proportion of "gap" responses on zero-gap trials) are used to define the ROC (Response Operating Characteristic) curve. These probabilities are used as indexes in a lookup table to obtain d', a measure of gap detectability. Next, d' is divided by two, which converts it to a z score for a $\beta=1$ criterion. This criterion corresponds to a symmetrical distribution of responses; that is, one at which there is no response bias (β is the likelihood ratio between HITS and FALSE ALARMS). Finally, the z score is converted to the proportion of area under the normal curve, which provides a normalized response under the symmetrical criterion. This procedure is carried out for each experimental condition. Note that the $P(C)_{max}$ procedure has been used previously by Craig (1984) in a tactile persistence study upon which this research is based.

The $P(C)_{max}$-transformed detections of the spatial gap were obtained for each condition in Experiment 1. These results are shown in Figure 4. It is evident that as ISI increases, performance declines. These observations were confirmed by statistical analysis.

Means of gap detection performance were examined using a two-way (stimulus duration and ISI) ANOVA.

As expected, a significant main effect of ISI obtained (F [5, 72] = 18.134, $p < .05$). Specifically, as ISI increases percent correct gap detection performance decreases. Post hoc analysis employing Tukey's HSD procedure revealed that performance in the 0 ms ISI condition differs significantly from that in the 50, 100, and 150 ms conditions; and the 5 ms and 10 ms ISI conditions both differ from the 100 and 150 ms conditions (HSD between means = 4.136, $p < .05$).

However, contrary to the storage hypothesis, stimulus duration also proved to be significant: F [3, 72] = 4.637, $p < .05$. Tukey's HSD showed that the 20 ms duration produced lower performance than all other durations; also, the 5 ms duration differs from the 15 ms duration (HSD between means = 5.338, $p < .05$).

Strength of association measures (estimates of the proportion of variance of the dependent variable accounted for by an independent variable) were also obtained for both of the above significant main effects. For ISI, it was found that estimated $\omega^2 = .47$ whereas for stimulus duration, estimated $\omega^2 = .06$. Note that although these values may be taken as evidence in favour of the storage hypothesis (i.e., ISI is more important to temporal integration than stimulus duration) it must be cautioned that these effects may have been influenced by the range of values chosen for the respective variables. That is, the stimulus duration merely ranges from 5 to 20 ms, whereas the ISI varies from 0 to 150 ms. Thus, the greater range of stimulus duration values may be responsible for the greater estimated strength of association than ISI. However, the fact that stimulus duration has a significant effect on performance must not be overlooked.

These results indicate that although gap detection performance is influenced by ISI, it is also affected by the duration of the leading stimulus. Because the storage model posits that the representation begins to decay at the offset of the stimulus, it cannot account for the effects produced by varying the stimulus duration. Based on the findings of this experiment, it is clear that a model that does not neglect the predictive power of stimulus duration in the temporal integration function is required.

EXPERIMENT 2

This experiment is designed to contrast the storage and processing models of tactile persistence. To that end, a form-part integration/spatial gap detection task is again employed, as in Experiment 1. The storage hypothesis, describing the representation as beginning to degenerate at stimulus offset, indicates that performance will decline with increasing ISI only. The processing model, on the other hand, posits that the representation of a stimulus begins to decay shortly after onset of the stimulus, thus neither the duration of the leading stimulus nor the ISI alone are considered to be as important as the SOA. The predictive power of the temporal variables of ISI and SOA is compared in this experiment, and that evidence is used to evaluate the relative utility of the storage and processing hypotheses.

Method

Subjects

The same observers from Experiment 1 participated in Experiment 2.

Apparatus

The same apparatus from Experiment 1 was also used in Experiment 2.

Stimuli

As in Experiment 1, a spatial gap of zero or two rows of inactive stimulators was presented between a pair of bars in each trial. To provide for a sufficiently broad range of response accuracy, the bars were presented for durations of 5, 10, 20, 40, 80, or 160 ms. ISIs between stimuli were 0, 25, 50, or 100 ms. The duration of the trailing stimulus was held constant at 15 ms.

Procedure

The procedure was the same as in Experiment 1.

Design

Experiment 2 was structured as a gap-detection task, designed as a 2 (gap size) × 6 (duration) × 4 (ISI) factorial experiment, with 48 separate conditions. As in Experiment 1, each participant collected 100 trials per data point in each condition; this experiment was also split into 50 sets, with 96 trials per set.

Hypotheses

As in Experiment 1, an examination of the percentage of correct responses in each experimental condition reveals the amount of temporal integration; from this information, the time-course of tactile persistence may be inferred. That is, the processing model stipulates that the representation begins to decay shortly after stimulus onset, as opposed to the offset-linked discharge of the storage model. Thus, the processing model predicts that the SOA between stimuli should account for a greater proportion of variance than the ISI. Specifically, it is predicted that as SOA increases, integration performance will decrease to asymptote at chance level; also, there should be poorer performance at longer durations within a given ISI value (inverse duration effect). The storage model fails to provide an account of the effects of leading stimulus duration.

According to the processing hypothesis, performance across conditions having the same SOA should be constant; further, there should not be differential results due to the particular duration/ISI combination that comprises the SOA. On the other hand, the storage hypothesis predicts that the condition having the shorter ISI will exhibit better performance. It is expected that the processing hypothesis will provide a better account of gap-detection performance than the storage hypothesis, a finding in accord with past research (e.g., Craig, 1983b).

Results and Discussion

Mean percent correct detections of the spatial gap were obtained for each experimental condition and were normalized by the $P(C)_{max}$ procedure as described above; these results are shown in Figure 5. It is evident that as SOA increases, performance declines; also, it appears that increasing duration lowers performance. These observations were confirmed by statistical analysis. Means of gap detection performance were examined using two analyses: a two-way (stimulus duration and ISI) ANOVA, and an ANOVA examining the effects of SOA. (Due to the non-orthogonality of SOA with respect to duration and ISI, it was required to perform a separate analysis of SOA.)

As expected, a main effect of SOA obtained (F [22, 73] = 2.428, $p < .05$). Stimulus duration was also determined to be significant (F [5, 72] = 5.728, $p < .05$). Post hoc analysis revealed that performance in the 160 ms condition differs from that in all other conditions but the 80 ms condition; also, the 80 ms condition differs from the 5, 10, and 20 ms conditions (HSD between means = 7.23, $p < .05$). A main effect of ISI also obtained (F [3, 72] = 4.350, $p < .05$). Specifically, performance in the 0 ms ISI condition was found to be better than that in the 100 ms condition (HSD between means = 4.58, $p < .05$).

Strengths of association were obtained for all of the above significant main effects. For SOA, estimated $\omega^2 = .25$, for stimulus duration, estimated $\omega^2 = .18$, and for ISI, estimated $\omega^2 = .08$. Clearly, SOA is a better predictor of performance than either ISI or stimulus duration alone, and it is as good a predictor as duration and ISI together (this latter finding is not unexpected, considering SOA is comprised of stimulus duration and ISI).

It is apparent that manipulating the range of values for stimulus duration and ISI does indeed affect performance, as evidenced by the fact that the relative effects of these variables are opposite what they were in Experiment 1. Note that in Experiment 2, the duration has a range of 5 to 160 ms, and the ISI has a range of 0 to 100 ms. This fact, however, merely supports the processing hypothesis further: it reinforces the significance of the roles of both duration and ISI in the tactile persistence function—at least inasmuch as they are both components of the SOA.

It is clear that the storage model is insufficient for conceptualizing tactile persistence. Although it was found to be significant, the temporal variable of ISI alone cannot describe performance as well as SOA; also, the storage model cannot account for the effects of stimulus duration. Finally, the curves of Figure 5 exhibit a degree of overlap that suggests that there is more variability between SOA conditions than there is within SOA conditions. However, the fact that there is any variability within a given SOA value must not be overlooked. The processing hypothesis itself may be superseded by another, stronger predictor of integration performance—perhaps even without incorporating the function of tactile persistence. The next experiment is applied to examine this possibility.

EXPERIMENT 3

This experiment is designed to compare the temporal correlation model and the processing hypothesis, again using a form-part integration task requiring observers to detect a spatial gap. The processing hypothesis predicts that performance will be the same across conditions having identical SOAs. However, the preceding experiment and other evidence (e.g., Loepelmann & Lechelt, 1993) indicates that this conception based on SOA alone insufficiently describes the phenomenon of temporal integration. The temporal correlation model posits that integration performance is based on a correlation between two (or more) temporally similar and contiguous stimuli; increasing the duration of the trailing stimulus is expected to lead to diminished performance, a prediction not specified by the processing model. Thus, performance across SOA values is compared, and the effects of manipulating the duration of the trailing stimulus are examined in an effort to garner evidence that the temporal correlation model has more predictive power in describing temporal integration than the processing hypothesis.

Method

Subjects

The same observers from Experiments 1 and 2 participated in Experiment 3.

Apparatus

The same apparatus from Experiments 1 and 2 was also used in Experiment 3.

Stimuli

To obtain a range of suitable results, durations of 5, 10, 20, 40, 80, or 160 ms were used for the trailing stimulus. ISIs between stimuli were 0, 25, 50, or 100 ms. The duration of the leading stimulus was held constant at 15 ms.

Procedure

The procedure was the same as in the above Experiments.

Design

Experiment 3 was again designed as a gap-detection task, with a 2 (gap size) × 6 (trailing stimulus duration) × 4 (ISI) factorial structure. Like the above experiments, there were 48 separate conditions. Participants each collected 100 trials per data point in each experimental condition; trials were again grouped into 50 sets of 96 trials.

Hypotheses

The percent correct responses in each experimental condition are again used to determine the amount of temporal integration. Comparisons are made among different trailing stimulus durations, within a given ISI value (note that in this experiment, SOA = ISI + 15 ms; i.e., SOA does not vary with the trailing stimulus duration). Because the duration of the leading stimulus is held constant, both the storage and processing models predict the same result: Performance will be the same in conditions sharing the same ISI (or SOA) values. These models do not take duration of the trailing stimulus into consideration.

On the other hand, the temporal correlation model predicts that performance within a given ISI will decrease as the duration of the trailing stimulus becomes more different from that of the leading stimulus. This manipulation has the effect of making the tactile response of the trailing stimulus more dissimilar from that of the leading stimulus, which produces a low correlation between the two. As a result, the stimuli will be coded as disjunct leading to poor integration, and thus poor gap detection performance. According to the temporal coding, it is expected that performance will decrease with increasing ISI, which also serves to decrease the correlation between the tactile responses of the leading and trailing stimuli.

Results and Discussion

Mean percent correct spatial gap detections were obtained for each experimental condition and were normalized by the $P(C)_{max}$ procedure; these results are shown in Figure 6. It is apparent that as the duration of the trailing stimulus increases, gap detection performance increases to a maximum, then decreases with the longer durations. This observation was confirmed by statistical analysis. Means of gap detection performance were examined using a two-way (duration of trailing stimulus and ISI) ANOVA.

As expected, in accord with the temporal correlation model, a main effect of duration of the trailing stimulus was obtained (F [6, 72] = 3.895, $p < .05$). Post hoc analysis using Tukey's HSD procedure revealed that the stimulus duration of 160 ms differs from all other conditions; as well, the 80 ms duration differs from the 5, 10, and 20 ms conditions (HSD between means = 5.90, $p < .05$). As expected, the main effect of ISI was also found to be statistically significant (F [4, 72] = 19.252, $p < .05$). Performance at 0 ms ISI was found to be better than that in the 100 ms condition (HSD between means = 6.79, $p < .05$).

The results of this experiment are clear evidence that the tactile version of the TCM provides a more complete account of integration performance than the processing hypothesis. Temporal coding correctly predicts that the duration of the trailing stimulus influences task efficacy—implying that the tactile persistence function may not be necessary to describe performance on a task requiring temporal integration. The suitability of the TCM remains to be seen, however, in a further condition in which an intrinsic persistence cannot be used to explain integration performance. This situation is examined in the next Experiment.

EXPERIMENT 4

This experiment is designed to provide further evidence for the temporal correlation model, which holds that the temporal pattern of a stream of stimuli is critical to temporal integration performance, and need not rely on an inferred decaying trace hypothesis. As in the previous experiments, a form-part integration task that requires observers to detect a spatial gap is used. Thus, in this experiment, the stimuli are presented with simultaneous onsets, and only the durations are varied. Again, neither the storage nor the processing hypotheses take the duration of the stimuli into account in this situation; indeed, the role of the tactile persistence function is not required.

Method

Subjects

The two male observers from Experiments 1, 2, and 3 also participated in Experiment 4. Two additional two male volunteers from the Department of Psychology served as observers: one had participated in previous experiments; the other had never used the OPTACON before. None of the observers had any experience using the OPTACON as a reading aid.

Apparatus

The same apparatus from the previous Experiments was also used in Experiment 4.

Stimuli

The SOA between stimuli in this experiment was held constant at 0 ms. Thus, there is no "leading" or "trailing" stimulus, with respect to temporal onset. This experiment was designed so that one stimulus (the trailing stimulus) is either as long as or longer than the other (the leading stimulus). For example, if the leading stimulus was 5 ms, the trailer could be 5, 10, 20, 40, 80, or 160 ms; but when the leader was 160 ms, the trailer could be only 160 ms. The durations used were 5, 10, 20, 40, 80, or 160 ms. For the sake of consistency, the terms "leading" and "trailing" are retained. (Note that the offset of the trailing stimulus occurs coinstantaneously with or after the offset of the leading stimulus, so the trailing stimulus can still be seen as being preceded by the leading stimulus.)

Procedure

The procedure was the same as in the above Experiments.

Design

Experiment 4 was again a gap-detection task. However, to ensure consistency between the descriptions of the stimuli as leading or trailing another (as described above), the experiment was not a full factorial design. Due to this manipulation, there were 21 temporally different experimental conditions, crossed with two different gap sizes (i.e., two-row gap or zero-row catch trials), producing 42 unique experimental conditions.

Each participant collected 100 trials per data point in each experimental condition; trials were grouped into 50 sets of 84 trials.

Hypotheses

Although both parts of the physical stimuli are presented with some extent of temporal overlap, the degree to which the bars are coded as coextensive may still be measured by examining the percentage of correct responses in each experimental condition. The processing hypothesis predicts equal performance across SOAs. However, because there is only one SOA value in this Experiment (i.e., 0 ms), this model predicts equal performance across *all* conditions. The storage model cannot even be applied to account for differential results under different conditions, as it relies solely on the ISI between stimuli—which is nonexistent in this Experiment. The only prediction implied by the storage model is consistently high performance across all experimental conditions. That these models—both based on an intrinsic-persistence framework—do not provide differential accounts of performance under the conditions of Experiment 4 is not surprising. The stimuli employed in this experiment were more simultaneous than sequential, the integration paradigm under which persistence is generally investigated. The temporal correlation model, on the other hand, can still be applied under these conditions: It predicts that integration performance will decline with increasing stimulus duration. Also, there should be poorer performance as the duration of one stimulus becomes more dissimilar from that of the other stimulus. Specifically, performance should decrease as the duration of the leading or trailing stimulus increases. Obtaining such results would support the TCM-based explanation in favour of an intrinsic persistence account of performance on a task requiring temporal integration.

Results and Discussion

Mean percent correct spatial gap detections were obtained for each experimental condition and were normalized by the $P(C)_{max}$ procedure. As shown in Figure 7, it is apparent that as the duration of the trailing stimulus increases from that of the leading stimulus, gap detection performance declines. Also, performance decreases with an increase in duration of the leading stimulus, as illustrated by Figure 8. These observations were confirmed by statistical analysis. Means of gap detection performance were examined using a two-way (duration of leading and trailing stimuli) ANOVA.

As expected, a main effect of duration of the trailing stimulus was obtained (F [5, 78] = 6.614, $p < .05$), in accord with the temporal correlation model. Post hoc analysis using Tukey's HSD revealed that the 5 ms condition exhibited greater performance than the 40, 80, and 160 ms conditions; and the 10 ms duration differs from the 160 ms condition (HSD between means = 15.042, $p < .05$). Also, a main effect of the duration of the leading stimulus obtained (F [5,78] = 14.120, $p < .05$). Post hoc analysis showed that performance in the 5 ms duration was better than that in the 20, 40, 80, and 160 ms conditions; further, 10 ms differs from 80 and 160 ms (HSD between means = 16.328, $p < .05$).

Strengths of association were obtained for the variables of duration, and for similarity of stimuli. Similarity is quantified as the absolute difference between the leading and trailing stimuli. For example, if the leading stimulus has a duration of 5 ms and the trailing stimulus has a duration of 5 ms, the difference is taken to be 0, indicating a high similarity between the stimuli. For stimulus duration, estimated $\omega^2 = .42$, whereas for stimulus similarity, estimated $\omega^2 = .15$. Clearly, stimulus duration is a much better predictor of performance than stimulus similarity.

It is clear that manipulating the duration of stimuli affects temporal integration performance—even on a task that does not require the presumed existence of some sort of tactile persistence to bridge a temporal gap between stimuli, as when the stimuli share a common onset time. Indeed, that performance on such a task is not accounted for by theories relying on an intrinsic persistence account provides support for the notion that an alternative explanation—such as the temporal coding hypothesis—may be more suitable.

GENERAL DISCUSSION

The above results reveal some of the shortcomings of models of tactile temporal integration based on an intrinsic persistence hypothesis. An alternative to these models is provided by the temporal correlation model (TCM), which employs a correlational mechanism to determine whether stimuli become temporally integrated. The predictive power of the TCM is evident in its capability to help account for existing empirical findings, as well as predict results in novel situations.

Although some of the findings of Experiment 1 seem to indicate support for tactile persistence as governed by the storage model, the results are far from incontrovertible. In accord with this model, a decline in performance with an increase in ISI was obtained. The notion of intrinsic persistence is used by the storage model to explain this effect: An internal representation of the leading stimulus is formed, constructing a sort of temporal "bridge" that persists in time until it is integrated with the representation of the trailing stimulus. Persistence is presumed to begin discharge at the offset of the leading stimulus; because reliable representations of both stimuli are not phenomenally available as the decay progresses, integration performance declines as the interval between stimuli increases. However, as seen in Figure 4, a drop in performance with increasing leading stimulus duration was also encountered: The inverse duration effect. As described by the storage model, persistence begins to degenerate at stimulus offset; thus, the temporal gap between stimuli is the critical variable influencing integration—the duration of the leading (or trailing) stimulus is not taken into consideration. It must be concluded, then, that because the effects of stimulus duration obtained in Experiment 1 are neglected, the storage model fails to provide an adequate account of performance.

One alternative to the storage model is the processing hypothesis, which is better suited to incorporating the effects of duration and ISI. Because this theory conceptualizes the internal representation as beginning to decay shortly after stimulus onset, the interval between onsets of successive stimuli is obviously important. The results of Experiment 2 essentially conform to predictions made by the processing model. The inverse duration effect again obtains: As the duration of the leading stimulus increases, performance decreases. Also, as shown in Figure 5, performance decreases as a function of increasing SOA. This outcome is to be expected if patterns are less likely to be integrated as the internal representation increasingly decays after the physical stimulus onset. According to the processing model, there should be minimal variation at any given SOA; however, a close examination of Figure 5 reveals a degree of variability of performance in conditions having the same SOA value. This result is supportive of the fact that, in successive stimuli, SOA is comprised of the sum of the leading stimulus duration and the ISI. Manipulating these components of the SOA produces differential results not predicted by the processing model. Indeed, an examination of the estimated strengths of association confirms the cumulative roles of duration and ISI with respect to SOA. It is not clear how a model employing a notion of intrinsic persistence can, in a straightforward manner, account for these findings; the conception of persistence applied by the processing model has relied on SOA to the neglect of stimulus duration and ISI. The TCM account, which does not rely on intrinsic persistence, was applied in anticipation that it would provide the basis for a more parsimonious account of temporal integration performance.

Neither the storage nor the processing model provides an account of the effects of trailing stimulus duration, due to their reliance on the notion of intrinsic persistence. However, before the direct effects of trailing stimulus duration in Experiment 3 are discussed, the ability of the intrinsic persistence-based models to account for effects on more customary temporal variables is examined. Figure 6 reveals a significant variation within a given ISI value that cannot be accounted for by the storage model. Note that in Experiment 3, SOA is merely the ISI plus a constant, so each curve in Figure 6 may be considered as also representing an SOA value. Thus this pattern of results is similarly problematic for the processing model: There is no explanation provided for the variation within a given SOA value. On the other hand, the TCM accounts for the effects of the temporal interval between stimuli, and the trailing stimulus duration. Figure 1 shows that as the temporal separation between the physical stimuli becomes larger, the correlation between neural responses (approximately corresponding to the shaded area) is decreased, increasing the likelihood that the stimuli will be coded as disjoint, and leading to a decline in temporal integration performance. The TCM also predicts that, all other things being equal, integration will be a maximum at the point at which the similarity between the leading and trailing stimuli is greatest. As seen in Figures 2 and 3, the correlation between neural responses of two stimuli (the shaded area) is high when the stimuli are of identical durations; this condition should produce a peak in temporal integration. Figure 6 reveals a peak close to 15 ms; performance is indeed greatest at the point of maximal similarity of stimuli, as predicted by a TCM-based account.

The utility of this version of the TCM under conditions not accounted for by the models based on intrinsic persistence was further tested in Experiment 4. Because the ISI was nonexistent, it was assumed that the storage model predicts uniformly high performance across all conditions; that the results obtained are in discord with the storage model is a telling disadvantage of the storage model. The SOA was held at 0 ms, which leads the processing model to predict consistent performance across conditions. As predicted by the TCM, an effect due to the longer or leading stimulus duration obtained (see Figure 8). There was also an effect of the trailing stimulus duration, as shown in Figure 7. Note that all these differences were obtained under a condition of 0 ms SOA, a finding not accounted for by the processing model. These results do, however, support the TCM: Even in conditions wherein the physical stimuli are temporally overlapping, the duration of each stimulus affects temporal integration. As shown in Figure 3, stimuli are also more highly correlated—and more likely to be coded as coextensive—when they are of similar duration. Although it is likely that the intermediary role of persistence is not required to explain performance due to "integration" of simultaneous stimuli, it is clear that the storage and processing models do not provide a satisfactory account of performance; predictions based on the TCM, however, are supported by the data.

It should be noted that differential effects of different variables were obtained. Specifically, the absolute values of stimulus duration were found to account for a greater proportion of the variance than the similarity between stimulus durations. This strong effect must not be overlooked. The role of these variables must be further quantified to increase the utility of the model, and allow empirical evidence to be more objectively compared with the model.

In sum, Experiment 1, ostensibly designed to provide support for the storage model, actually revealed results inconsistent with predictions in that variability was observed within an ISI due to leading stimulus duration. Experiment 2, ostensibly intended to reveal positive evidence for the processing hypothesis, also showed its deficiency in accounting for the results: Variability within a given SOA due to the particular leading stimulus duration/ISI combination indicated that these latter variables needed to be taken into consideration to give a more complete account of performance. Experiment 3 illustrated that, although SOA does explain some of the results, the effects of the duration of the trailing stimulus were neglected; the TCM, though, did account for the findings. Lastly, Experiment 4 showed that neither the storage model nor the processing model could account for performance under conditions of onset simultaneity and differing stimulus duration.

It is apparent that the experiments in this study reveal the limited generalizability of models predicated on the idea of intrinsic persistence to a wide range of conditions under which temporal integration obtains. In contrast, the TCM, relying on a correlational coding process, is better suited to explaining these effects. The fact that the TCM can be applied under these unique conditions serves to exemplify the wide-ranging predictive power of this model.

Part of the utility of the TCM is its ability to explain phenomena that are not accounted for by intrinsic persistence models. According to intrinsic persistence models, for example, moving stimuli should produce trails of "motion smear" as they travel across the display. One of the advantages of the TCM, on the other hand, is that it provides an account of the dualism of temporal stimulation. Multiple proximal stimuli on the skin may be produced by either a) repeated presentations of the same distal stimulus, or b) single presentations of a number of different distal stimuli. Intrinsic persistence accounts do not explain how the perceptual system differentiates between these two cases. The TCM, though, allows the two situations to be separated based on the assumption that repeated stimulation caused by one particular distal stimulus will have the same temporal profile. According to the TCM, when brief proximal stimuli have similar temporal profiles, they are coded as coextensive; produced by a common distal stimulus. When stimuli on the skin have sufficiently different temporal characteristics, they are coded as temporally segregated; they are not perceived as integrated, but rather as produced by separate sources. Thus, the TCM serves to separate temporal phenomena, furnishing a means of determining whether stimuli should be coded as coextensive or disjoint.

The Look and Feel of Integration

Theoretical and empirical progress in delineating the phenomenon of temporal integration of tactile stimuli has shadowed advances in the visual domain. The relatively simplistic conception of visible persistence provided by the storage model was eventually superseded by the more sophisticated processing model. The latest development in attempting to describe and explain the phenomenon is the TCM, which was necessitated by the decreasing predictive utility in the burgeoning variety of conditions under which temporal integration occurs. In the tactile domain, the story has unfolded in a similar manner: the storage model was employed until the weight of evidence caused it to be rejected in favour of a processing account. Until now, though, tactile SOA-based models have not been called into question. But the evidence presented above reveals the advantages of a correlational model inspired by work in the visual domain.

This similarity in the development of visual and tactile accounts of temporal integration may not be coincidental. The possibility must be considered that the processing of temporal information in both senses is accomplished using similar underlying mechanisms. By examining the assumptions upon which the visual and tactile versions of the TCM is based, it may be revealed how information is processed in comparable ways across these modalities. For example, the TCM requires that the stimuli must be temporally filtered.

Temporal integration may occur between the sensations of two physical stimuli which do not overlap in time. Indeed, under such conditions, any correlation between the physical stimuli would be null. Rather, the TCM assumes the samples of activity that form the basis of the correlation between stimuli are taken from the neural responses produced by the physical stimuli. The neural responses differ temporally from the physical stimuli in that they are formed shortly after the onset and continue considerably well past the offset of the inducing physical stimulus.

There is evidence at several levels indicating that the visual response is indeed delayed in time, and outlasts the stimulus. For example, photoreceptor depolarization lasts several milliseconds; it has also been found that a stimulus lasting less than 1 ms produces activity in the striate cortex lasting 100 ms (see Dixon & Di Lollo, 1994). Thus the activity of the early visual system (and, it is assumed, the visual responses) can be formally described by the output of a linear temporal filter. Comparing simulations of the TCM based on linear systems theory with empirical data, it was found that the two were in accord (Dixon & Di Lollo, 1994)—a result that served to further reinforce the TCM.

To remain in accord with the TCM, the response functions of the tactile sense need conform to three general specifications: 1) the tactile responses must be delayed in time relative to the physical stimuli, 2) they must continue for some time (i.e., not merely locked to stimulus onset and offset), and 3) responses to temporally successive physical stimuli must overlap in time. Darian-Smith (1982) noted that most cutaneous neurons in the primary (SI) and secondary (SII) somatosensory areas of the cerebral cortex exhibit response characteristics corresponding to one of the peripheral nerve fibres. This finding implies that cortical neurons receiving input from rapidly adapting fibres show activity only at stimulus onset or offset, and are quiet during the stimulus itself. However, with OPTACON stimulation, the firing of peripheral RA fibres continues with the application of the stimulus (Gardner & Palmer, 1989a; 1989b). There is also evidence that rapidly adapting channels show both latency and sustained activity in the cortex. The RA afferent channels, positively identified as being activated by the OPTACON display, have been found to manifest a latency in peak activity of 4 to 10 ms after OPTACON stimulus onset

(Gardner & Palmer, 1989a). Evidence of both latency and sustained activity were obtained in single-unit recordings in areas 3b and 1 of SI as a response to brief airpuffs, which activated the RA channel only. The elicited activity exhibited a latency of 11-12 ms, and lasted another 15-20 ms (Gardner & Costanzo, 1980; Gardner, Hämäläinen, Warren, Davis, & Young, 1984). Rosner (1961) also found prolonged activity in the thalamus and SI resulting from peripheral nerve stimulation, although it is unclear which fibre type was stimulated. Some of this response latency is explained by the conduction velocity of the Aβ cutaneous nerve fibres: a moderate 35 to 75 m/s (Johnson & Lamb, 1981; Martin & Jessell, 1991). It has been suggested that a duration of activity in the somatosensory cerebral cortex of about 0.5 s is required before an awareness of stimulation on the skin is formed (Libet, Wright, Feinstein, & Pearl, 1992), further supporting the contention of the temporal endurance of the neural responses.

The similarity between the tactile and visual systems in temporal processing is further supported by evidence that the tactile responses can also be described as the output of a linear temporal filter. Martin (1991) noted that connective tissue comprising the Pacinian corpuscle (also triggered by the OPTACON), functions as a spatiotemporal filter that dampens steady pressure or low frequency vibrations. In a review of the application of linear systems analysis to the tactile sense it was noted that: "In the context of touch, the essential idea is that the earlier stages of cutaneous processing can be conceived as constituting a spatiotemporal filter acting upon the stimulus that is applied to the skin" (p. 31-4, Loomis & Lederman, 1986). It is noted that there is no single overall temporal filter for a given body locus, because the filter function depends on such varied and variable factors as contactor size, the state of adaptation of the observer, and the temperature of the skin. Thus it may be quite difficult, if not impossible, to specify the precise linear filter function of the tactile sense. However, the goal of this paper is not to provide a quantitative model, but a qualitative one.

The evidence presented above suggests that there are similarities in the processing of information between domains, but there may even be areas of the brain that process impinging stimuli from multiple modalities. For example, research has uncovered neurons that respond to both visual and tactile input. It has been found that cells in area VIP (ventral intra-parietal) are sensitive to motion, similar to cells in MT and MST (motion-sensitive vision regions in the superior temporal sulcus), and are also activated by tactile motion (Duhamel, Colby, & Goldberg, 1991). These neurons may play a role in a supra-modal representation of space. It may be that there also exists a brain region dedicated to a form of temporal processing that is common to multiple modalities. Stein and Meredith (1993) uncovered multisensory neurons in the superior colliculus of the cat that exhibited latency and sustained activity in response to visual and tactile stimulation; temporal integration of successive stimuli was obtained in these cells.

The limbic system, the most primitive area of the brain, has been implicated in synesthesia, the phenomenon that occurs when the stimulation of one sense modality spontaneously produces sensation in another (Cytowic, 1989). Synesthesia is different from imagery: Some sensations simply lend themselves to description in other-modality terms; for example, a certain piece of music may be described as "bright" or "dark." Those experiencing synesthesia, though, may describe the taste of chicken as having a discrete number of points, like a geometric shape; or hearing the name "Francis" produces a sensation like the taste of baked beans (Ackerman, 1990). Because of its low rate of incidence (those who experience intense synesthesia number 1 in 500 000) and large individual differences, synesthesia has proved difficult to study empirically in a systematic manner (Cytowic, 1993). This phenomenon raises the question of whether there exist tactile stimuli which are associated with the percept of certain alphabetic letters. If so, it would be advantageous to present not just as a replica of the visual stimulus that represents *E*, but also the "feeling" or "sense" of the letter *E*. Until the processes underlying synesthesia are better understood, such presentation of stimuli will remain a tantalizing possibility.

By investigating the functional similarities in the processing of stimuli across modalities, not only may a better understanding of the phenomenon of temporal integration be obtained, but such information could also contribute to a more integrated conception of brain functioning.

IMPLICATIONS AND CONCLUSIONS

The implications of the TCM may be applied to reading aids like the OPTACON; both static (non-moving) and dynamic (moving) modes of presentation are considered. In static mode, letters are individually presented successively on the OPTACON's tactile display. The TCM predicts that to cause successive letters to be perceived as disjoint (to facilitate reading), each letter would have to differ along one or more temporal dimensions in comparison to the immediately preceding or succeeding letters. This outcome may be achieved by increasing the ISI between letters and/or increasing the duration of one stimulus relative to another. Because one of the goals of sensory substitution is the rapid transmission of information, the option of simply increasing the ISI is an unattractive (and unnecessary) one. It may be possible to obtain a rapid reading rate by presenting successive stimuli for differing durations, with an ISI of 0 ms. For example, the first letter may be presented for 40 ms, followed immediately after by the next letter for a duration of 80 ms. The next letter would again be presented for 40 ms. By altering the duration of a letter relative to preceding and following letters, temporal integration may be minimized, without the cost of significantly increasing overall presentation time.

Applying the TCM to the dynamic mode of presentation is a more complex matter than in the static mode. Motion is produced on the display of the OPTACON by presenting a succession of frames, each of which displaces the position of the letter by a small amount relative to the previous frame—a sort of apparent motion. According to the TCM, the perceptual integrity of a moving letter is maintained by the similarity in temporal profile of successive frames. Although some degree of integration is presumably necessary to maintain the perceptual integrity of the moving letter (i.e., so that the train of frames is not perceived as a series of separate, discrete patterns), it is important to minimize the integration between letters.

Intuitively, one may expect the basic unit of visually presented linguistic material ("graphemes") to be letters. However, it has been found that certain letter combinations are processed together as a whole (Healy, 1976). Specifically, in familiar words like *the*, multiple letter units like *th* are read as a single unit (Healy, Oliver, & McNamara, 1982). It is not surprising then, to discover that increasing the number of letters viewed at once produces an increase in the rate of visual reading (Gibson & Levin, 1975). In the tactile domain, Taenzer (1970) found that a wider display increased the reading rate of visual and tactile letters. However, at its maximum width, only one letter could be displayed at a time. In further research extending a tactile display over two fingers and doubling the size of the display contacting a single finger, no benefits to the reading rate were obtained (Hill,1974). At this point, no conclusion can be made as to whether this effect is due to a basic sensory limitation of the skin or to a higher-level inability to process multiple tactile letters as a single unit.

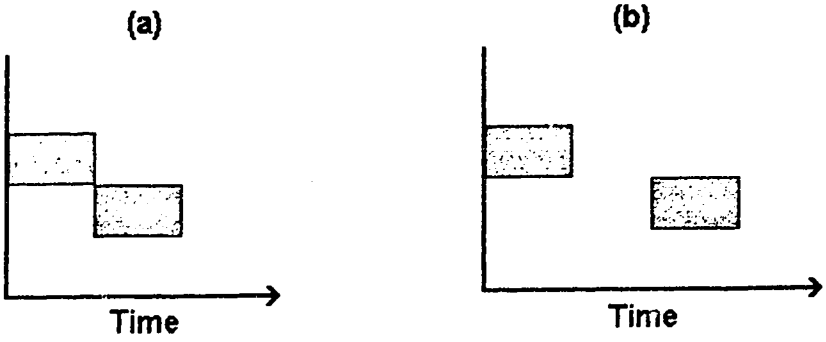
When used normally for reading, the OPTACON displays information in dynamic mode; at any given time, parts of more than one letter may simultaneously occupy the display. That is, the right half of the letter *T*, for example, may be exiting the left part of the display while the left half of the next letter in the word, say, *H*, emerges from the right half of the display. As a result, the separability of these two letters may be problematic at greater presentation rates; conversely, the readability may be improved by increasing the presentation time; either way, the readability/presentation time tradeoff again obtains. In this situation, the temporal characteristics of each *letter* must be controlled independently (as opposed to manipulation of the entire *frame*, which may contain more than one letter at a given time). If the OPTACON is being used alone in real time to scan across a page of printed text with the miniaturized digitizing camera, complex spatiotemporal manipulations would not be possible. However, with the OPTACON interfaced with a computer, it would be trivial to use static mode to display tactile information that was acquired by moving the digitizing camera across a page. Indeed, such a transformation may be beneficial, as suggested by evidence that static displays produce better reading performance than some dynamic ones (Craig, 1982). Nonetheless, the application of the TCM to dynamic displays is examined.

Consider this example: The TCM implies that to have stimuli coded as disjoint, they should have maximally different durations; the more similar the duration, the more likely stimuli will be coded as coextensive. Thus, integration may be minimized by presenting one letter for frames of a duration of 20 ms, and the succeeding letter for durations of 40 ms as it moved across the display. However, this manipulation would likely suffer a high cost of presentation time: Every other letter is being presented for much longer than the minimum time necessary to identify it. A more careful interpretation of the implications of the TCM reveals that it would be possible to present stimuli with a temporal profile that a) maintains the integrity of each letter, b) maximizes separability between letters, and c) minimizes overall presentation time. To do this, the first frame of each letter would be presented for a short duration; for example, 10 ms. The next frame would have a slightly longer duration, but no so long that it is coded as disjoint from the first frame (e.g., 15 ms); in this way, the TCM is used to preserve the integrity of each letter. The lengthening of the duration of successive frames continues until the final frame. Meanwhile, the next letter of the word will have appeared on the display. This letter would also obey the temporal profile of increasing duration. Thus, even if two letters are on the display at the same time, each will be presented for a significantly different amount of time (e.g., 100 ms vs. 10 ms), minimizing the likelihood that two letters will become integrated. This method would also serve to minimize the overall presentation time: no one letter is presented for an inordinately long period of time. It has been found that in dynamic mode, masking had the greatest effect on recognition of a target letter that was spatiotemporally located between two nontarget letters, showing both forward and backward masking due to temporal integration (Sherrick, 1982). It is likely that the manipulations described above would decrease the deleterious effects of masking in this situation. In this way, a satisfactory tradeoff in the goals of sensory substitution may be achieved; namely, that of maximizing the perceptibility of the stimuli in the auxiliary modality, and minimizing the presentation time.

The series of studies reported has provided some evidence in favour of a model of tactile temporal integration, based on the temporal correlation model. The fact that this version of the TCM may be used to explain and describe temporal integration phenomena not accounted for by models based on the intrinsic persistence hypothesis serves to reinforce its utility. In its current form, the TCM does not provide an account of how information is processed spatially, or how positional information is reconciled with the location of a stimulus in space—this question needs to be addressed to obtain a fully satisfactory explanation of perceptual processing. But perhaps the most interesting result of employing the TCM in the tactile domain is that in the processing of temporal information, vision and touch seem to share a functionally similar temporal mechanism. Past attempts at applying information originating in the visual domain to the tactile realm have revealed that the differences between the two senses are greater than their similarities. It is clear that the skin cannot be treated as a tactile retina; the tactile modality is unable to process the vast quantities of information in parallel that the visual system handles so effortlessly. Indeed, the skin understands a language of its own. However, the existence of commonalities between domains must not be overlooked. These similarities allow us not only to better understand the processing of information in each sense, but may also serve to facilitate the translation of information from one modality to another. It is clear that the conversion of information from one language to another requires that the translator is fluent in both the source and target languages. So too must those working towards the goal of sensory substitution be able to effortlessly understand the languages of the senses.

Figure 1: (a) Physical stimuli are not separated by a temporal gap; (b) stimuli separated by a gap.

Physical Stimuli



Neural Responses

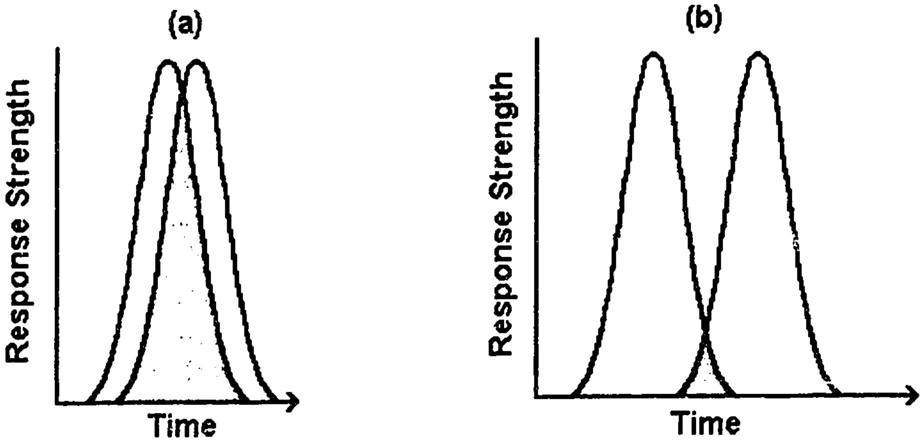


Figure 2: (a) Physical stimuli have identical durations; (b) leading stimulus has a greater duration than the trailing stimulus.

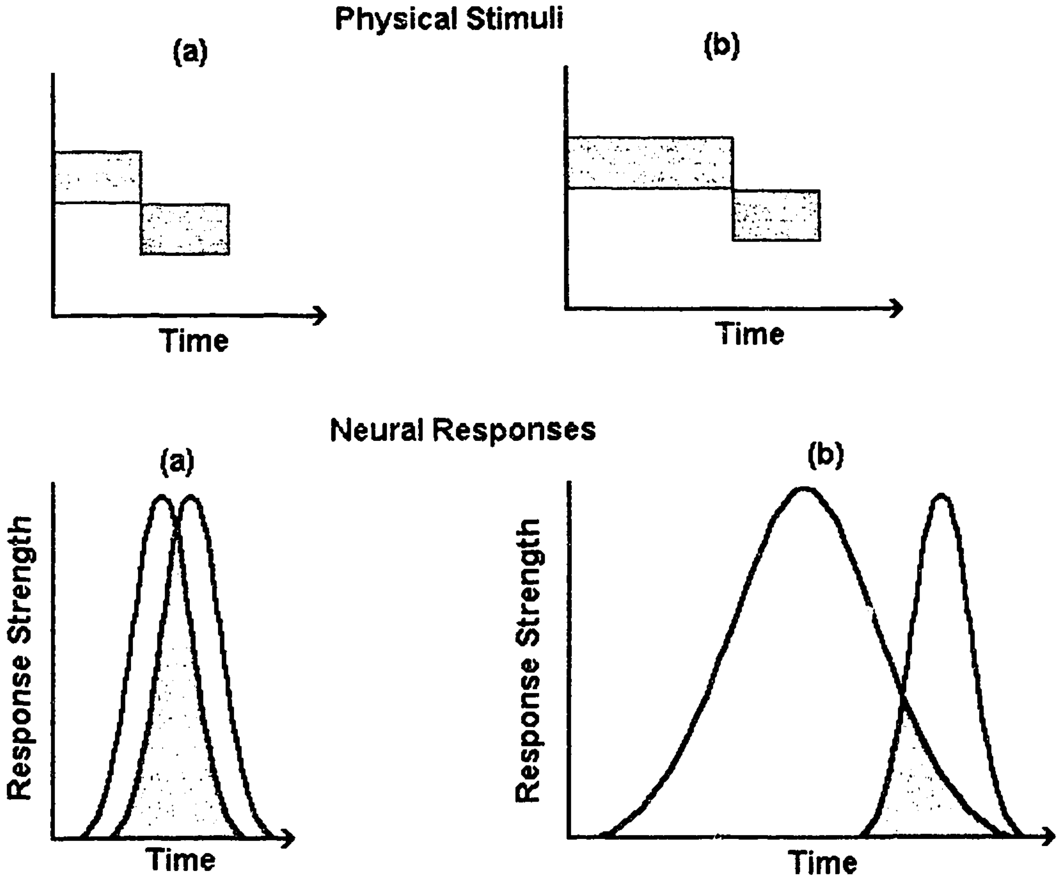


Figure 3.(a) Physical stimuli have identical durations; (b) trailing stimulus has a greater duration than the leading stimulus.

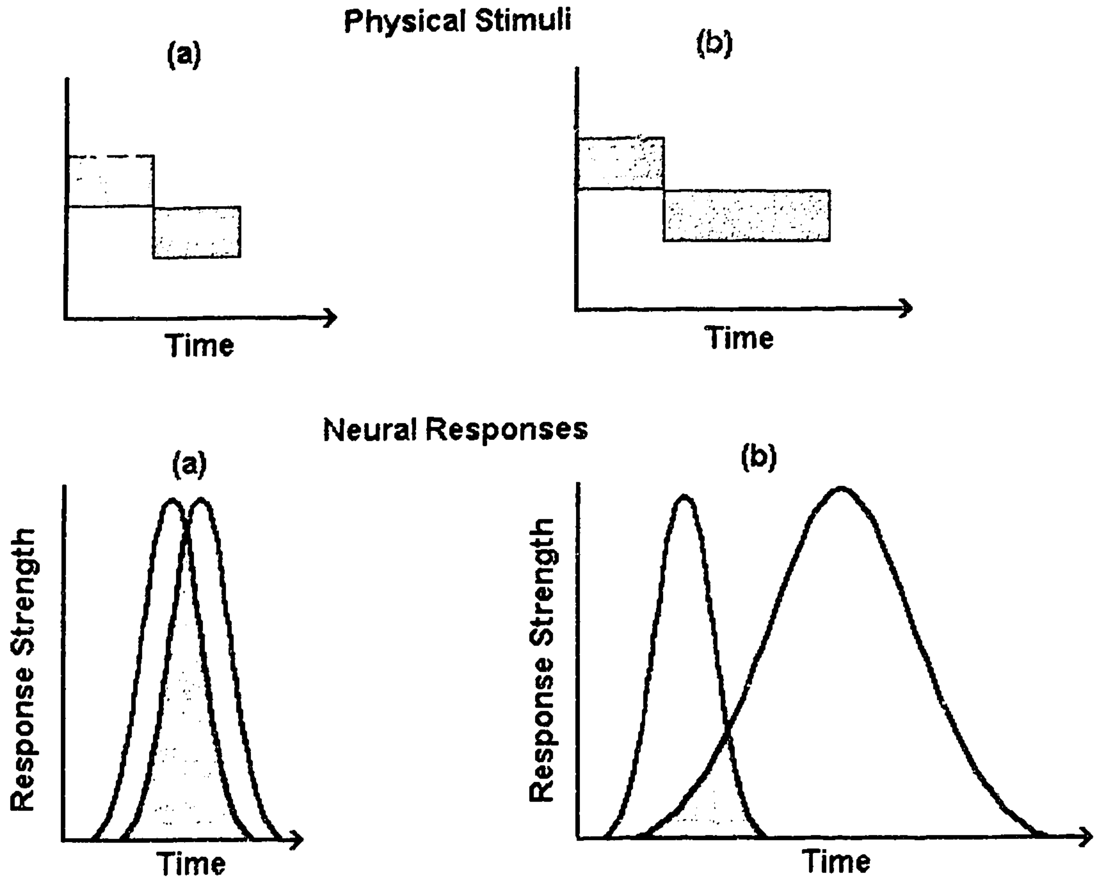


Figure 4: Gap detection performance as a function of ISI.

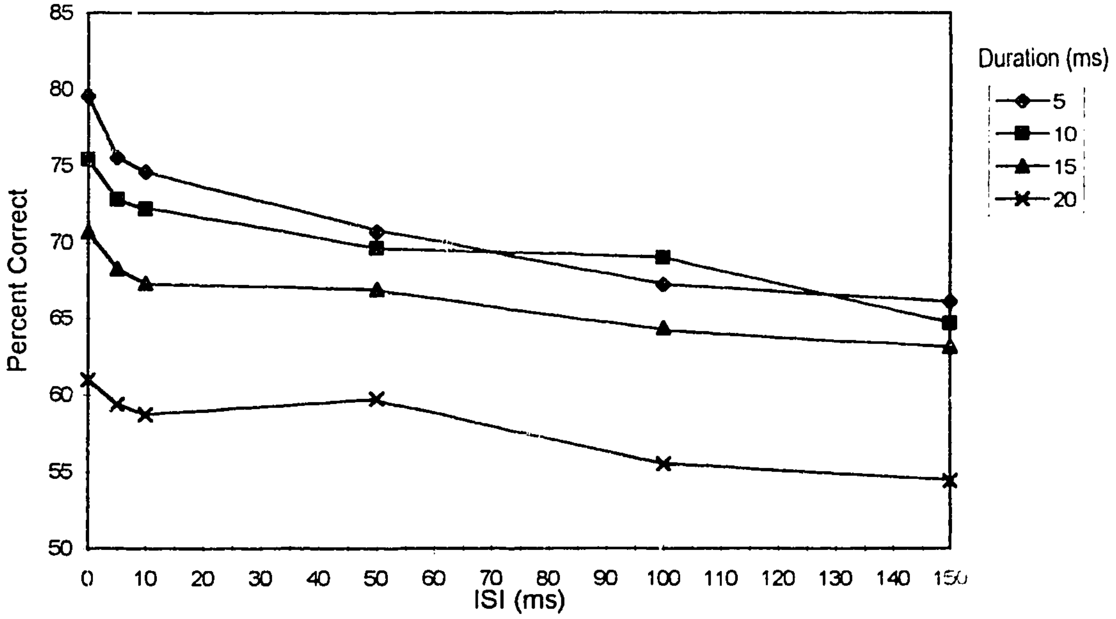
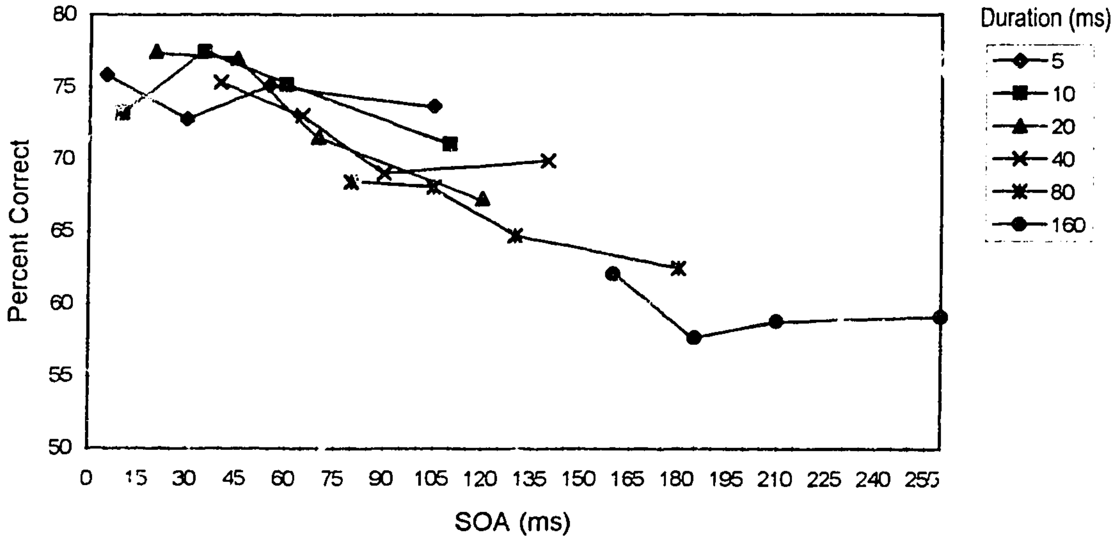


Figure 5: Gap detection performance as a function of SOA.



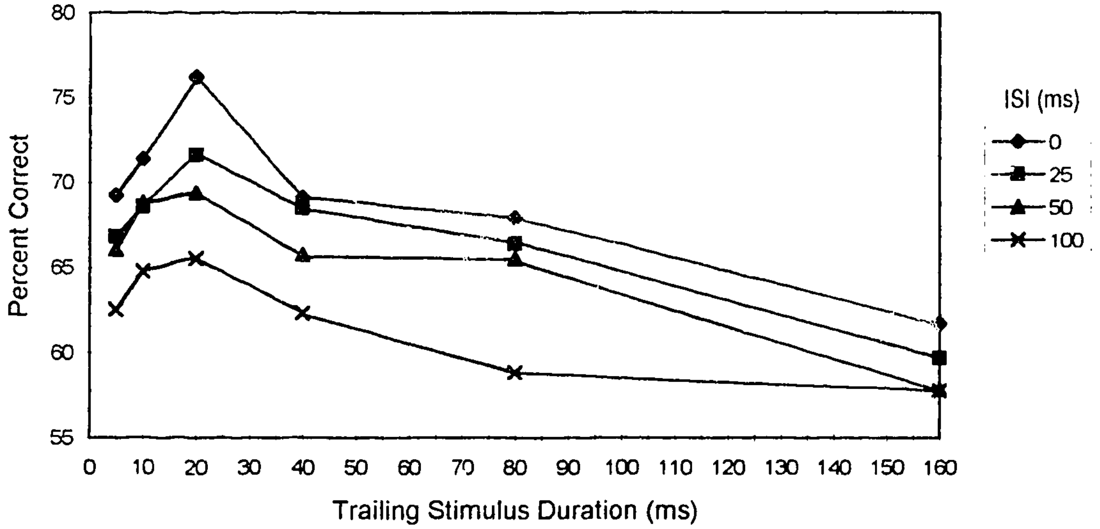


Figure 6: Gap detection performance as a function of trailing stimulus duration.

Figure 7: Gap detection performance as a function of the duration of the longer stimulus, at 0 ms ISI.

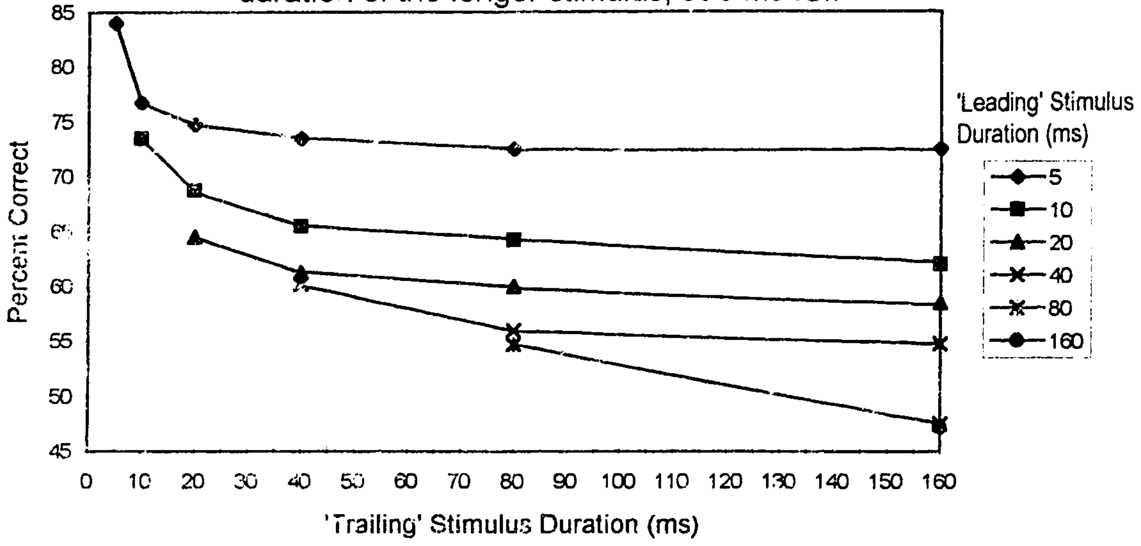
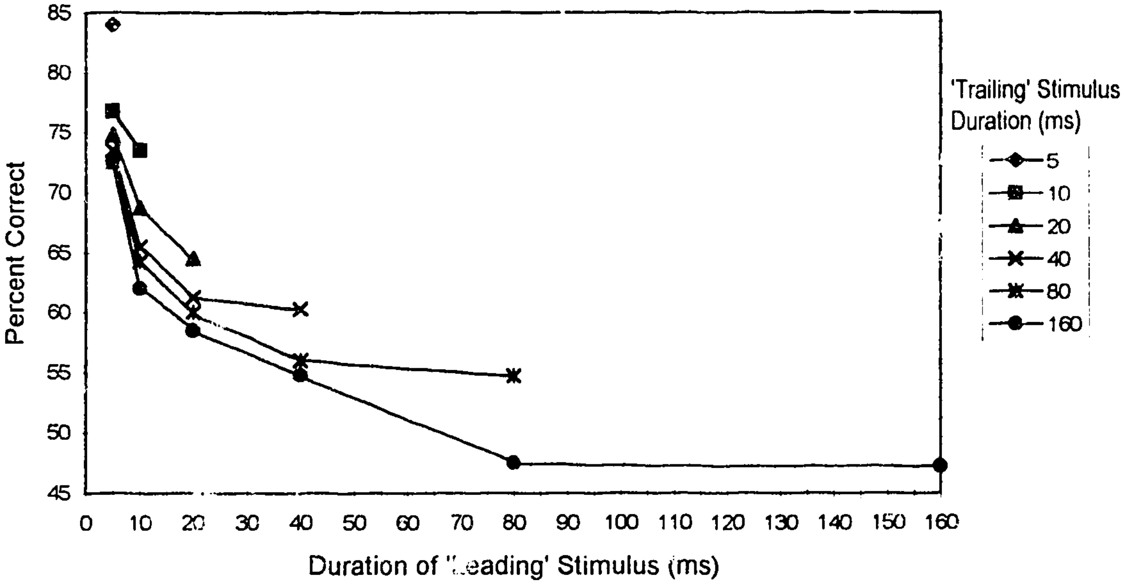


Figure 8: Gap detection performance as a function of the duration of the shorter stimulus, at 0 ms ISI.



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