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This project concerned the discovery and description of basic mechanisms of human visual motion and texture perception. Motion and texture are critical inputs to visual perception. Basic mechanisms of motion are of particular interest because they are perhaps the primary substrate for perceptual recovery of 3D depth structures and orientation in space, they are critical for detecting new objects and events in the environment, as well as play-ing an important role in 2D perception. Motion and texuture are considered together here because the problem of discriminating velocity in a one-dimensional motion stimulus is formally equivalent to the problem of discriminating orientation in a texture stimulus: the t dimension of the motion stimulus becomes the y dimension of the texture stimulus.

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Sperling: Visual Motion Perception and Visual Information Processing

~~FINAL~~ Annual REPORT AFOSR Grant 91-0178

February 1, 1992 to January 31, 1993 (includes unfunded extention to 31Dec93)

ABSTRACT

This final progress report summaries the main recent results; full reports of the results are contained in the papers appended herewith. The summary also reviews some results from previous AFOSR grants where these are necessary to provide the background for the current research. Four areas are summarized:

1. Basic Mechanisms of Visual Motion and Texture Perception
2. Lateral Interations in Texture Stimuli
3. Information Processing
4. Visual Attention and Short-Term Memory.

1. Basic Mechanisms of Visual Motion and Texture Perception

This project concerned the discovery and description of basic mechanisms of human visual motion and texture perception. Motion and texture are critical inputs to visual perception. Basic mechanisms of motion are of particular interest because they are perhaps the primary substrate for perceptual recovery of 3D depth structures and orientation in space, they are critical for detecting new objects and events in the environment, as well as playing an important role in 2D perception.

Motion and texture are considered together here because the problem of discriminating velocity in a one-dimensional motion stimulus is formally equivalent to the problem of discriminating orientation in a texture stimulus: the t dimension of the motion stimulus becomes the y dimension of the texture stimulus.

First-Order Motion Perception

First-order motion perception. The initial studies, carried out at the inception of AFOSR support, succeeded in describing the basic mechanism of human Fourier motion perception in full mathematical detail. Several critical insights made this possible. The most important was recognizing that the failure of previous theoretical attempts to apply Reichardt (1957) and similar systems models to human vision (e.g. Foster, 1971) was due in large measure to the fact that they had dealt with data obtained with high-contrast visual stimuli. The human motion-processing system behaves in a simple way for stimuli whose contrast is less than about 0.04 to 0.05 (e.g. Nakayama & Silverman, 1985, others). For higher contrasts, early nonlinearities in the visual system make the analysis the motion processing enormously more complex. Additionally, because hundreds of thousands of detectors may contribute to human psychophysical responses, formal models need to explicitly model decision processes. Finally, stimuli needed to be developed that permitted conclusions about basic motion computations independent of the voting/decision rules imposed by higher-order processes.

van Santen & Sperling (1984) was perhaps the first successful application of these basic principles first-order motion perception to humans, principles that are now quite widely accepted. van Santen & Sperling (1985) showed the equivalence of two subsequent models (Adelson & Bergen, Watson & Ahumada) to the van Santen-Sperling version of the Reichardt model and it developed new results.

van Santen, J. P. H. and Sperling, G. (1984). Temporal covariance model of human motion perception. *Journal of the Optical Society of America - A, 1*, 451-473.

The first of two papers by van Santen and Sperling reports that, by elaborating a Reichardt model that had previously been proposed for insect vision, the model gives an excellent account of human psychophysical data for low-contrast stimuli. To apply a Reichardt detector to human vision requires in considering voting rules (e.g., absolute maximum or total power) for detectors because many detectors present possibly conflicting information to the decision stage. There is a full mathematical development of the elaborated theory. Many counter-intuitive predictions were generated by the theory, and three were experimentally tested. (1) A superimposed stationary grating, even of a grating the same spatial frequency as a moving grating, should not adversely affect motion-direction discrimination. (2) Similarly, a stationary flickering grid should have not affect motion discrimination of a moving stimuli with different temporal frequency. When temporal frequencies of the moving and masking stimuli are the same, then anything may happen, even an illusion of motion in the opposite direction. This apparent reversal of direction of the moving grating for certain predicatable phase relations of the masking stimulus was demonstrated experimentally. (3) For certain spatially-sampled displays, the strength of a motion percept is directly proportional to the *product* of the contrast in adjacent regions. All three predictions were verified. These data show that, contrary to "logical intuition," human motion detection does not rely on matching spatial features in successive frames, but rather on matching of temporal sequences in adjacent locations.

van Santen, J. P. H. and Sperling, G. (1985) Elaborated Reichardt detectors. *Journal of the Optical Society of America - A, 2*, 300-321.

This paper extends the predictive power of the elaborated Reichardt model from continuous to two-flash stimuli, and to other displays, such as random dot displays, that had previously been thought to require "feature" models. It points out that the Reichardt model is consistent with a 3D spatiotemporal Fourier analysis of visual displays. However, when complex displays contain several Fourier components of approximately equal perceptual strength, a more complex analysis such as that of the elaborated Reichardt model, is needed to generate predictions. For example, displays in which component Fourier components move in the same direction and at the same temporal frequency exhibit as more convincing movement than displays in which the components move at the same velocity so to preserve 2D rigidity. It was proved that, for elaborated Reichardt detectors, the strength of motion in two flash displays is predicted by separable temporal and spatial components, so that these displays are ideal for studying the pure spatial properties of motion detectors. Finally, it was proved that two alternative computational theories (Adelson & Bergen, 1985 and Watson & Ahumada, 1985) for which no experimental data had yet been generated, were computationally equivalent to the elaborated Reichardt model.

Investigations of Second-Order Motion and Texture

The theoretical analysis and experimental evidence described above establishes an elaborated Reichardt (or equivalent kind of motion computation) as the basic mechanism of motion perception. The work of the current granting period dealt with a newly discovered second mechanism of motion perception, which was called "Second-order" or "Non-Fourier" motion processing to distinguish it from the previously described "First-order" or "Fourier" motion perception. The computational principles that applied to second-order motion perception were found also to apply to the perception of two-dimensional textures.

Chubb, Charles, and George Sperling. (1988). Drift-balanced random stimuli: A general basis for studying non-Fourier motion perception. *Journal of the Optical Society of America A: Optics and Image Science, 5,* 1986-2006.

This paper sets forth the general principles. It shows how to construct counterexamples to first-order motion computations: visual stimuli which (i) are consistently perceived as obviously moving in a fixed direction, yet for which (ii) Fourier domain energy analysis yields no systematic motion components in any given direction. A general theoretical framework for investigating nonFourier (second-order) motion-perception mechanisms; two central concepts are *drift balanced* and *microbalanced* random stimuli. A random stimulus S is *drift balanced* if its expected power in the frequency domain is symmetric with respect to temporal frequency: that is, if the expected power in S of every drifting sinusoidal component is equal to the expected power of the sinusoid of the same spatial frequency, drifting at the same rate in the opposite direction. Additionally, S is *micro balanced* if the result WS of windowing S by any space-time separable function W is driftbalanced. It is proved that (i) any space/time separable random (or nonrandom) stimulus is microbalanced; (iia) any linear combination of a pairwise independent microbalanced random stimuli is microbalanced, and any linear combination of a pairwise independent driftbalanced random stimuli is driftbalanced if the expectation of each component is zero (a uniform field); (iii) the convolution of independent micro/driftbalanced random stimuli is micro/driftbalanced; (iv) the product of independent microbalanced random stimuli is microbalanced. Examples are provided of classes of driftbalanced random stimuli which display consistent and compelling motion in one direction although they would be completely ambiguous to any first-order motion mechanism. The perception of nonFourier motion stimuli is explained by postulating a linear space-invariant filter followed by a rectifying mechanism that computes (any increasing function of) the absolute value of stimulus contrast followed by Fourier-energy (e.g., Reichardt) motion analysis. All the results and examples from the domain of motion perception are transposable to and illustrated in the space-domain problem of detecting orientation in texture patterns.

Chubb, Charles, and George Sperling. (1989). Second-order motion perception: Space-time separable mechanisms. Proceedings: Workshop on Visual Motion. (March 20-22, 1989, Irvine, California.) Washington, D.C: IEEE Computer Society Press. Pp. 126-138.

This paper shows how various classes of microbalanced displays can be used to derive properties of second-order motion systems. *Microbalanced* stimuli are dynamic displays which do not stimulate mechanisms that apply *standard motion analysis* directly to luminance (e.g., Adelson-Bergen motion-energy analyzers, Watson-Ahumada motion sensors, or elaborated Reichardt detectors.) Because they bypass *first-order* mechanisms, microbalanced stimuli are uniquely useful for studying *second-order* motion perception (motion perception served by mechanisms that require a grossly nonlinear stimulus transformation prior to standard analysis). The paper demonstrates stimuli that are *microbalanced under all pointwise stimulus transformations* and therefore immune to early visual nonlinearities. Such stimuli are used to disable motion information derived from spatial filtering in order to isolate the temporal properties of space/time separable second-order motion mechanisms. They are equally useful to disable the motion information derived from temporal filtering to isolate the spatial properties.

The paper proposes that second-order motion of all of the classes of microbalanced stimuli under consideration can be extracted by a mechanism consisting of the following stages: (1a) band-selective spatial filtering and (1b) biphasic temporal filtering, nonzero in dc, followed by (2) a rectifying nonlinearity and (3) standard motion analysis.

Chubb, Charles, and George Sperling. (1989). Two motion perception mechanisms revealed by distance driven reversal of apparent motion. *Proceedings of the National Academy of Sciences, USA, 86,* 2985-2989.

It is reasonable to ask whether there really are two mechanisms of motion perception or whether one theory can encompasses both. One way to demonstrate the existence of two mechanisms is to stimulate them to simultaneously give opposite outputs in response to the same stimulus. This paper demonstrates two kinds of visual stimuli that exhibit motion in one direction when viewed from near and in the opposite direction from afar. These striking reversals occur because each kind of stimulus is constructed to simultaneously activate two different mechanisms: a short-range mechanism that computes motion from space-time correspondences in stimulus *luminance* and a long-range mechanism whose motion computations are performed, instead, on stimulus contrast that has been full-wave rectified (e.g., the absolute value of contrast). The stimuli were constructed so that half-wave rectification could be excluded. It is concluded that both a Fourier and a nonFourier computation occur. In this and all previously studied cases of 2nd order motion perception, full wave rectification has been shown to be a *sufficient* mechanism; for these stimuli, full wave rectification (versus half-wave rectification) is shown to be *necessary*.

An analogous phenomenon, distance-driven reversal of apparent slant, occurs with texture stimuli. Apparently, in both motion and texture extraction from visual scenes, there are two parallel mechanisms, operating simultaneously, a first-order mechanism that operates directly on the Fourier components of the stimulus, and a second-order mechanism that operates on a spatiotemporally filtered, full-wave rectified transformation of the stimulus.

Chubb, Charles, and George Sperling. (1991). Texture quilts: Basic tools for studying motion-from-texture. *Journal of Mathematical Psychology, 35, 411-442.*

This paper continues the investigation of motion-from-spatial-texture in stimuli that are free from contamination by motion mechanisms sensitive to anything except texture. It offers a formal foundation for some of the results outlined in Chubb & Sperling's (1989) IEEE paper, and reports the results of three demonstration experiments that establish empirical properties of human second-order motion perception. Additionally, some concrete stimulus-construction methods are provided for a special class of random stimuli called *texture quilts*. Although, as is demonstrated experimentally, certain texture quilts display consistent apparent motion, it is proven that their motion content (a) is unavailable to standard motion analysis (such as might be accomplished by an Adelson/Bergen motion-energy analyzer, a Watson/Ahumada motion sensor, or by any elaborated Reichardt detector), and (b) cannot be exposed to standard motion analysis by any purely temporal signal transformation no matter how nonlinear (e.g., temporal differentiation followed by rectification). Applying such a purely temporal transformation to any texture quilt produces a spatiotemporal function P whose motion is unavailable to standard motion analysis: The expected response of every Reichardt detector to P is 0 at every instant in time.

Three quilts were studied experimentally: a quilt that relies on differences in spatial frequency to generate perception of motion, a quilt that relies on sensitivity to differences in orientation, and quilt that relies on the difference between an even texture and a jointly-independent random texture. The simplest mechanism sufficient to sense the motion exhibited by texture quilts consists of three successive stages: (i) a purely spatial linear filter (ii) a rectifier to transform regions of large negative or positive responses into regions of high positive values, and (iii) standard motion analysis. The first quilt demonstrates that the spatial filter is frequency selective. The second quilt demonstrates that there exist orientation selective filters. The third quilt demonstrates that the rectifier cannot embody a perfect squaring (power) function.

Werkhoven, Peter, George Sperling, and Chubb, Charles. (1993). The dimensionality of texture-defined motion: A single channel theory. *Vision Research, 33, 463-485.*

This paper explores texture-defined motion between similarly oriented sinusoidal patches. It exploits two ambiguous motion displays (types I and II) in each of which apparent motion can be perceived in either of two directions. One of these directions is along a homogeneous space-time path in which all successive sinusoidal patches are identical in spatial frequency and contrast. Along the other, oppositely directed, path is composed of heterogeneous patches that vary in spatial frequency and contrast. The striking and counterintuitive result is that for a wide variety of display conditions, perceived motion along the heterogeneous path dominates the homogeneous path. Obviously, when perceived motion along a path composed of alternating high- and low-frequency patches dominates perceived motion along a pure high-frequency path, the strength of texture-defined motion is not governed by a similarity metric.

All the results are explained in terms of an activity transformation. Each patch is assumed to cause a perceptual response (activity). Strength of perceived motion along a path is determined by the product of the activities of adjacent patches along the path. The path with the greatest product dominates.

Whenever a particular combination of patch contrasts and spatial frequencies caused the two motion paths to be balanced in displays of type I, then they were found to be also balanced in type II displays, a condition referred to as *transition invariance*. Under quite reasonable assumptions about the motion mechanism, it was shown that transition invariance implies that activity must be a one-dimensional quantity. Indeed, activity is well-described as the rectified output of a spatial low-pass filter.

Werkhoven, Peter, Charles Chubb, and George Sperling. (1994) Perception of Apparent Motion between Dissimilar Gratings: Spatiotemporal Properties. *Vision Research. (Accepted for publication pending revisions.)*

This paper continues the search for the determinants of the perceptual strength of texture-defined motion (i.e., motion strength of stimuli that have no net directional energy in the Fourier domain). Werkhoven, Sperling, & Chubb (1993) demonstrated that *correspondence* in spatial frequency and contrast between neighboring patches of texture in a spatiotemporal motion path is irrelevant to motion strength, only *activity*—the rectified output of a spatial lowpass filter—mattered. As in Werkhoven et al (1993), the motion stimuli are ambiguous motion displays in which one motion path, consisting of patches of nonsimilar texture, competes with another motion path, having patches only of similar texture. The textural parameters of spatial frequency, contrast, texture orientation (slant), and temporal frequency are systematically explored.

The data show that motion between dissimilar patches of texture (which are orthogonally oriented, have a two octave difference in spatial frequency and differ 50% in contrast) can easily dominate motion between similar patches of texture. The relative motion strengths of two paths is invariant with temporal frequency from 1 to 4 Hz. Analysis of the data shows that the motion computation is largely but not entirely one-dimensional: Extreme orientation differences and very large spatial frequency differences bring into play small but significant contributions of a second dimension (or dimensions).

2. Lateral Interactions in Texture Stimuli: Contrast-Contrast

Chubb, Charles, George Sperling, and Joshua A. Solomon. (1989). Texture interactions determine perceived contrast. *Proceedings of the National Academy of Sciences, USA, 86,* 9631-9635.

Various visual illusions that have been demonstrated for first-order stimuli, may be expected to have corresponding second-order illusions. When the illusions are the result of important properties of signal processing, such as boundary enhancement and gain control, the corresponding second-order illusions should be quite informative about the corresponding second-order process.. This paper considers the second-order analog to perhaps the most famous first-order lightness illusion, namely that the apparent lightness of a uniformly illuminated patch depends on the luminance of its surround. Here it is reported that the perceived *contrast* of a test patch P of binary visual noise embedded in a surrounding noise field S depends substantially on the *contrast* of S. When P is surrounded by high-contrast noise, its bright points appear dimmer, and simultaneously, its dark points appear less dark than when P is surrounded by a uniform field, even though local mean luminance is kept constant across all displays. Sinusoidally modulating the contrast P_S of the noise surround S causes the apparent contrast of P to modulate in antiphase to C_S. For P of contrast C_p, nulling procedures show that the induced induced contrast modulation of P reaches 0.45 C_p. This very large, heretofore unnoticed, spatial interaction is unanticipated by all current theories of lightness perception. It suggests a very general principle of perceptual computation: gain control. Gain control may be be a nearly universal process whereby the response of all a detector is normalized relative to the responses of their neighbors in the same and similar classes.

Joshua A. Solomon and George Sperling. (1993). The lateral inhibition of perceived contrast is indifferent to on-center/off-center segregation but specific to orientation. *Vision Research, 33,* 2671-2683.

Chubb, Sperling, and Solomon (1990) showed that the perceived contrast of a test patch of isotropic spatial texture P embedded in a surrounding texture field S, depends substantially on the contrast of the texture surround S. When P is surrounded by a high contrast texture with a similar spatial frequency cont :nt, it appears to be have less contrast than when it is surrounded by a uniform field. This paper describes two novel textures: T^+ which is designed to selectively stimulate only the on-center system, and T^-, the off-center system. When the type of C and of S is chosen to be T^+ or T^-, the reduction of C's apparent contrast does not vary with the combination of T^+, T^-. This demonstrates that the reduction of C's apparent contrast is mediated by a mechanism whose neural locus is central to the interaction between on-center and off-center visual systems.

The induced reduction of apparent contrast is shown to be *orientation specificity*: the reduction of grating C's apparent contrast by a surround grating S, of the same spatial frequency is greatest when C and S have equal orientation. Using dynamically phase-shifting sinusoidal gratings of 3.3, 10 and 20 cpd, the reduction of apparent contrast was measured using different contrast-combinations of C and S.

The results: (1) Both parallel and orthogonal S gratings caused suppression of P's apparent contrast relative to a uniform surround. (2) In all of the viewing conditions, the reduction of apparent contrast induced by the parallel surrounds was at least as great as that induced by the perpendicular surrounds. Often it was much greater (orientation specificity). (3) Orientation specificity increased with greater spatial frequencies and with lower stimulus contrasts. The results suggest a contrast perception mechanism in which both oriented and nonoriented units determine the perceived lightness or darkness of a point in visual space, and every unit is inhibited primarily by similar adjacent units.

3. Information Processing: Frequency Bands, Subsampling, Noise; Space and Object Perception

This cluster of projects determined, in several domains, how to most efficiently package information to an observer. Obviously, issues of external representation of information are inextricably tied to the question of "What internal representation does the observer use?" Such investigations may lead to useful formulations of how to improve both information presentation and observer training. The basic method was to partition the total stimulus information into several spatial frequency bands, and to determine performance individually for the component bands. Additionally, Riedl and Sperling studied cross-band masking and measure how information from component frequency bands combines in a complex, dynamic visual stimulus.

The "Three-stages and two systems" paper in this sequences proposes a theoretical analysis of the basic computations of visual preprocessing. It shows how results from motion and texture discrimination experiments derive from the same mechanisms that serve higher-order object object perception. The eye movement paper in this sequence deals with the internal representation of scenes that derive from a sequence of saccadic eye movements, and with the visual mechanisms that serve the saccadic mode of information acquisition.

Sperling, Wurst & Lu deal with a new method of discriminating early from late attentional filtering of features that occur within at a single location . Their paradigm, which was applied to repetition detection task, is easily be extended to visual search, and this forms the basis of the proposed experiments.

Riedl, Thomas R. and George Sperling. Spatial frequency bands in complex visual stimuli: American Sign Language *Journal of the Optical Society of America A: Optics and Image Science,* 1988, *5,* 606-616.

This project examined dynamic images of individual signs of American Sign Language (ASL) with a resolution of 96 × 64 pixels which were bandpass filtered in adjacent frequency bands. Intelligibility was determined by testing deaf subjects fluent in ASL. (a) It was possible to find four adjacent bands which divided the signal into approximately equally intelligible parts, any one of which yielded adequate identification accuracy (a) By iteratively varying the center frequencies and bandwidths of the spatial bandpass filters, it was possible to divide the original signal into four different component bands of high intelligibility (67-87% for isolated ASL signs). (b) The empirically measured temporal frequency spectrum was approximately the same in all bands. (c) The masking of signals in band i by noise in band j was found to be proportional to the frequency similarity: $\log |(f_{noise} / f_{signal})\Delta\omega|$ At constant performance, $(RMS)_{signal} / (RMS)_{noise}$ was the same for bands 2, 3, 4 and higher for band 1. (d) The most effective masking noise is slightly lower in spatial frequency than stimulus ($\Delta\omega$=1.4). (e) Intelligibility for the sum of two very weak signals is greater the closer they are in spatial frequency; for strong signals, the reverse is true. The dominant factor for weak signals is square-law additivity of signal power; for strong signals, redundancy within a band is the limiting factor.

Parish, David H. and George Sperling. Object spatial frequencies, retinal spatial frequencies, noise, and the efficiency of letter discrimination. *Vision Research,* 1991, *31,* 1399-1415.

The 26 upper-case letters of English were used to determine which spatial frequencies are most effective for letter identification, and whether this is because letters are objectively more discriminable in these frequency bands or because observers can utilize the information more efficiently. Six two-octave wide filters produced spatially filtered letters with 2D-mean frequencies ranging from 0.4 to 20 *cycles per letter height.* Subjects attempted to spatially filtered letters in the presence of identically filtered, added Gaussian noise. The percent of correct letter identifications was measured as a function of s/n in each band at each of four viewing distances ranging over 32:1. In this paradigm, *object spatial frequency band* and s/n determine *presence of information* in the stimulus; *viewing distance* determines retinal spatial frequency, and affects only *ability to utilize.* (a) Viewing distance had no effect upon letter discriminability: object spatial frequency, not retinal spatial frequency, determined discriminability. (b) With the assistance of Charles Chubb, an ideal detector was computed for the letter identification task. For these two-octave wide bands, s/n performance of humans and of the ideal detector improved with frequency mainly because linear bandwidth increased as a function of frequency. (c) Human discrimination efficiency (which compares human discrimination to an ideal discriminator) was 0 in the lowest frequency bands, reached a maximum of 0.42 at 1.5 cycles per object, and dropped to about .104

in the highest band. (d) Upper-case letter information is best extracted from spatial frequencies of 1.5 cycles per object height, an with equal high efficiency over at least a 32:1 range of retinal frequencies from .074 to more than 2.3 cycles per degree of visual angle.

Parish, David H., George Sperling, and Michael S. Landy. Intelligent temporal subsampling of American Sign Language using event boundaries. *Journal of Experimental Psychology: Human Perception and Performance,* 1990, *16,* 282-294.

This paper investigates the effects of temporal stimulus subsampling and the form of stimulus representation on intelligibility of a complex visual stimulus (American Sign Language). How well can a sequence of ASL frames be represented by a subset of the frames, and how is the subset optimally chosen? Two drastically different representations of frame sequences were investigated: *dynamic* (ordinary video viewing) and *static* (component frames placed side-by-side in a single display). Secondarily, full gray scale images were compared with binary images (cartoons). An *activity-index* was used to select critical frames at event boundaries–moments in the sequence where the difference between successive frames has a local minimum. Identification accuracy (intelligibility) was measured for 32 experienced ASL signers who viewed 84 variously constructed sequences of isolated ASL signs. With dynamic sequences that utilized full gray-scale, activity-index subsampling yielded significantly more-intelligible sequences than simple repetition of every *n*-th frame, achieving relative compression ratios of up to 2:1. For static sequences, activity subsampling with a small, optimal number of frames achieved higher intelligibility than was achieved by choosing every *n*-th frame, for any *n*. Binary images were less intelligible than the gray scale images, and the relative advantage of activity subsampling was smaller.

(1) Event boundaries can be defined computationally. Sequences composed of frames chosen from event boundaries yielded higher intelligibility than sequences composed of equal numbers of frames spaced at regular intervals. (2) Static presentation of subsets of selected frames can yield intelligible ASL "text" of isolated signs and perhaps, eventually, of conversational ASL.

This research opens the general question of how to use printing technology in place of video technology, where the printing technology is enhanced at the point of production by computer graphics techniques. How can an automatically generated sequence of images best be used -- like a comic book -- to represent a dynamic sequence of events. When an artist is required to represent the images for eventual printing, the cost can be prohibitive. When the images can be automatically generated from a video recording, the production costs are minor. The ASL study demonstrates the feasibility of representing a dynamic ASL sign by a simultaneously visible packet of images. Research is needed to determine how these results might be generalized to more complex communications and to practical training problems that involve dynamic actions.

Sperling, George. Three stages and two systems of visual processing. *Spatial Vision,* 1989, *4,* 183-207.

This paper offers a theoretical synthesis of classic work on light adaptation and on visual thresholds for pattern stimuli, work on efficiency of identification in various spatial frequency bands, and work on motion and texture perception, in terms of three stages and two systems of visual processing. The initial question is: How would an internal noise (at various levels of perceptual processing) appear to external observer? This is determined by the internal location of the noise relative to three stages of visual processing: light adaptation, contrast gain control, and a postsensory/decision stage. Dark noise occurs prior to adaptation, determines dark-adapted absolute thresholds, and mimics stationary external noise. Sensory noise occurs after dark adaptation, determines contrast thresholds for sine gratings and similar stimuli, and mimics external noise that increases with mean luminance. Postsensory noise incorporates perceptual, decision, and mnemonic processes. It occurs after contrast-gain control and mimics external noise that increases with stimulus contrast (i.e., *multiplicative* noise). and therefore mimics external multiplicative noise. Dark noise and sensory noise are frequency specific and primarily affect weak signals. Only postsensory noise significantly affects the discriminability of strong signals masked by stimulus noise; postsensory noise has constant power over a wide spatial frequency range in which sensory noise varies enormously. Especially in dealing with modulation transfer functions, there has been considerable confusion over the spectrum of internal sensory noise (which unavoidably depends on spatial frequency) with the gain factor of sensory transmission (which ideally would be independent of spatial frequency).

Two parallel perceptual regimes jointly serve human object recognition and motion perception: a first-order linear (Fourier) regime that computes relations directly from stimulus *luminance*, and a second-order nonlinear (nonFourier) rectifying regime that uses the absolute value (or power) of stimulus *contrast*. When objects or movements are defined by high spatial frequencies (i.e., texture *carrier* frequencies whose wavelengths are small compared to the object size), the responses of high-frequency receptors are *demodulated* by *rectification* to facilitate discrimination at the higher processing levels. Rectification sacrifices the statistical efficiency (noise resistance) of the first-order regime for efficiency of connectivity and computation.

Sperling, George. Comparison of perception in the moving and stationary eye. In E. Kowler (Ed), *Eye Movements and their Role in Visual and Cognitive Processes.* Amsterdam, The Netherlands: Elsevier Biomedical Press, 1990. Pp. 307-351.

This paper reports the construction of an apparatus for producing *simulated* saccades--continuous sequences of images on a stationary retina that are equivalent to the images produced on the retina during saccadic eye movements. Spatial localization was studied for stimuli flashed during real eye movements (using a limbus monitor) and during identical image sequences (simulated saccades) produced on a stationary retina. The comparison between real and simulated saccades gives critical insights into those mechanisms that are particular to saccades. The paper reviews the historically important paradigms (and representative experiments) that purport to deal with special modes of saccadic processing. On the basis of all these data, it proposes a theory to account for saccadic simulation experiments and to deal with such questions about human visual perception as:

Why don't we see the smear produced on the retina during an eye movement?

Why doesn't the world appear to move as a result of the image movements produced by eye movements?

Does the visual system require sudden stimulus onsets (such as those produced by eye movements) to initiate processing episodes?

To serve the perceptual construction of a stable representation of the world, is there a special memory to relate images produced by successive eye movements?

Sperling, G. Wurst, S. A., and Lu, Z-L. (1993). Using repetition detection to define and localize the processes of selective attention. In D. E. Meyer and S. Kornblum (Eds.), *Attention and Performance XIV: Synergies in Experimental Psychology, Artificial Intelligence, and Cognitive Neuroscience - A Silver Jubilee* Cambridge, MA: MIT Press. Pp. 265-298.

Can subjects selectively attend to a subset of items in rapid display sequences, when the subset is characterized by an obvious physical feature, but all items occur in the same location. The paradigm is a repetition detection task in which subjects search a very rapidly presented sequence of thirty superimposed frames for an item that is repeated within four frames. Successful detection implies that a match occurs between an incoming item and a recent item retained in short-term visual repetition memory (STVRM). Previous results (Kaufman, 1978, Wurst, 1989) showed that detection of visual repetitions in a rapid stream of items is indifferent to eye of origin and to interposed masking fields, and functions as well for nonsense shapes as for digits. Therefore, STVRM is visual, not verbal or semantic. It is governed by interference from new items; it does not suffer passive decay within the short interstimulus intervals under which it has been tested.

This paper uses a novel elaboration of a repetition detection paradigm. Within the stream, the physical features of the successive items alternate in color, size or spatial frequency. For example, in the size condition, the odd-numbered items in the stream are large and the even-numbered items are small. Subjects attend selectively to *small* (or to *large*) items. Using selective attention instructions with the repetition detection task permits testing the extent to which, at a single location, subjects can filter rapidly-successive items according to their physical characteristics. By presenting all the items at the same location, only attentional selection according to features (and not according to location) is effective. Subjects selectively attended to subsets of characters based on physical differences of orientation, contrast polarity, color, size, spatial bandpass filtering, and polarity-and-size combined.

Results. Efficiency of attentional selection was determined by comparing performance in a stream of characters that alternated a physical feature with performance in two control conditions: One in which the to-be-unattended characters were optically filtered and another in which all characters shared the same physical feature. Selection efficiency in bandpass filtered streams and in the polarity-and-size streams was greater than 50 percent. Attentional selection based on the other physical features was less effective or ineffective.

Corresponding to the benefits of attentional selection in detecting to-be-attended repetitions, there were large costs in the detection of unattended features. Costs were more ubiquitous than benefits.

In addition to studying repetitions of items that shared a physical feature (homogeneous repetitions) heterogeneous repetitions were studied. Costs for detecting heterogeneous repetitions (relative to homogeneous repetitions) were widespread, indicating that physical features are represented in STVRM. The corresponding stimulus benefits of detecting homogeneous repetitions in feature-alternating streams (under equal attention) were small and only occasionally significant.

If the state of attention were represented in STVRM, we would expect a cost in the detection of heterogeneous repetitions with selective attention instructions (because the attentional state would differ for the two elements of the pair). Such costs were observed and, in some instances they occurred even when there was no corresponding benefit for selective attention in homogeneous detections. This was interpreted as a lack of early attentional filtering compensated by a memory tag representing whether or not an item was attended.

Conclusion: The largest attentional effects occur at the level of attentional selection prior to encoding in STVRM (for bandpass and polarity-and-size stimuli) but that, even when early attentional filtering fails, it can still occur in STVRM.

4. Visual Attention and Short-Term Memory

Performance in many visual tasks depends not only on characteristics of the visual system, but also on more cognitive processes involved in processing visual information, such as attention and memory. The experiments seek to dissect the processes involved in short-term attentional control and the corresponding short-term memory systems. The experimental methods mostly involve rapid sequences of displays because our past work has shown that temporal sequences can be used to sample the time course of temporal processing. The work on visual persistence, iconic memory, and related phenomena exemplifies processing in the absence of successive events; i.e., single-event processing.

Background

The attention experiments herein and many prior experiments from the vast literature on visual attention are encompassed in a general theoretical framework. The starting point is the first published demonstration of an attentional operating characteristic (Sperling and Melchner, 1976, 1978a) and the concept of attentional resources developed by Navon and Gopher (1979), Norman and Bobrow (1975), and others.

Sperling, G. A unified theory of attention and signal detection. In R. Parasuraman and D. R. Davies (Eds.), *Varieties of Attention.* New York, N. Y.: Academic Press, 1984. Pp. 103-181. A state of attention is characterized by a particular allocation of processing and mnemonic resources, and this allocation determines the joint performance on two (or more) competing tasks. The Attention Operating Characteristic (AOC) is the range of possible joint performances as resource allocation is varied from one extreme to the other. This paper demonstrates that the AOC is generated by a process that is mathematically equivalent to the process that generates the receiver operating characteristic (ROC) of signal detection theory (i.e., the process partitions observations into either signal or noise response categories).

This article also proposes a formal definition of a task as a triple of two sets (stimuli and responses) and a mapping between them (a utility function). The task definition enabled a distinction between *compound* and *concurrent* tasks. Concurrent tasks were shown to be especially useful in the study of attention, whereas compound tasks involved primarily the study of decision making, and resulted in considerable difficulties when they were applied to attention. The utility function (in the task definition) is essential to understanding human performance. In contemporary, formal theory, "utility" plays the same role as did "purpose" in earlier, informal accounts of behavior.

Sperling, G., and B. A. Dosher. (1986). Strategy and optimization in human information processing. In K. Boff, L. Kaufman, and J. Thomas (Eds.), *Handbook of Perception and Performance. Vol. 1.* New York, NY: Wiley, 1986. Pp. 2-1 to 2-65.

This highly condensed, encyclopedic treatment of a large literature on attention and performance is equivalent to over 200 ordinary book pages plus more than 100 figure panels. Concepts such as formal task definitions, compound and concurrent tasks, attentional resources, attentional operating characteristics, and more generally, strategies to optimize performance, are applied to the interpretation of data from many classical paradigms. This yields a deeper understanding and, in many instances, vastly different conclusions.

Attentional Trajectories.

The Wilson Cloud Chamber and Glaser Bubble Chamber, which are designed to make visible the trajectories of individual atomic and subatomic particles, work by populating the volume within which a particle will move with steam or superheated liquid. When a target particle moves thru the chamber, a few of the molecules it strikes form the nucleus of condensing droplettes or evolving bubbles, and the visible track of these droplettes or bubbles defines the trajectory.

Sperling and Reeves (1980) introduced an analogous procedure in the realm of measurements of human attention. A rapid stream of superimposed visual items was presented at rates of up to 13 per second in a single spatial location. Subjects attended a second location. At a critical moment during the sequence, subjects were cued to execute a shift of attention to the stream location, and to report the earliest four of the items. The historgram (distribution) of the actually reported items (a small fraction of the presented items) defined the rapid growth and subsequent decline of attention at the stream location. This paradigm made it possible to measure reaction times of shifts of visual attention. Indeed, the paradigm allows the measurement not only of the mean reaction time of an attentional shift but of the entire density function of attentional reaction times (ARTs). Mean ARTs were shown to be quite similar to motor reaction times (MRTs) and to covary with MRTs in response to factors such as task difficulty and target predictability.

Reeves, A., and G. Sperling. (1986) Attention gating in short-term visual memory. *Psychological Review, 93,* 180-206.

This paper offers a computational model of a shift of visual attention, greatly enlarging on the procedures of Sperling & Reeves (1980). An attention shift takes attention from its initial location a to a second location b. While attention is focussed at a, stimulus information from a is admitted to further processing, and stimulus information from b is excluded. After the shift, the roles of a and b are reversed. The process of shifting attention to b is conceptualized as the opening of an attentional gate at b. In Reeves and Sperling's (1980) attentional task, location b contains a rapid stream of characters, so the attention gate remains open at b only for a for a brief period to avoid flooding memory with irrelevant items.

The theory assumes that the fraction of stimulus information passed on to higher mental processes from a location in space and a moment in time is proportional to the attentional allocation at that location. The theory contains only three parameters: First, there is a latency between the signal to shift attention and the start of the attention shift. Second, the time course of gate opening is described by a second-order gamma function with a time constant, typically, of several hundred msec. Third, there is the amplitude of internal noise that determines the signal-to-noise ratio of the internally represented information.

The data set is quite complex, and the theory makes accurate predictions of literally hundreds of data points with these few parameters.

Sperling, George. The magical number seven: Information processing then and now. In William Hirst (Ed.), *The making of cognitive science: Essays in honor of George A. Miller.* Cambridge, UK: Cambridge University Press, 1988.

This article analyzes why the magical number 7 +-2 had such a major impact on cognitive science --it is the most cited experimental/theoretical article in Psychology. The article 7+-2 offers a theoretical account of absolute judgment (sensory categorization) experiments and of short-term memory experiments. Both kinds of experiments have a limit of 7 (bits, and items, respectively). There are no self-citations in the references. All of the evidence Miller used was publically available. Miller, like Sherlock Holmes, was the one who was able to formulate a theory to encompass these data, and it was perhaps the first plausible quantitative theory to deal with the microprocess of cognition.

The second part of the analysis deals with the current status of Miller's proposals. Miller's seven-item limit turns out to depend on factors such as acoustic confusability, implying that the item limit is based on a sensory-based acoustic memory rather than an abstract memory. The review then points out that a single memory system--a stack of seven items--can encompass both the bit and the item limits Miller had proposed. In a sensory categorization experiment, the seven items in working memory are items with-respect-to-which new items are judged. In a short-term recall experiment, they are the to-be-recalled items. Such a stack memory is easily embodied in a neural network. Thus, a simple neural network memory model can encompass the two main tenets of Miller's magical number seven.

Weichselgartner, E., and George Sperling. (1987) Dynamics of automatic and controlled visual attention. *Science, 238,* 778-780.

Uses the Sperling & Reeves (1980) paradigm to isolate and measure the partially concurrent time courses of automatic and controlled attentional shift. The automatic component is extremely rapid, very brief in duration, and relatively effortless. The controlled component has the same time course as the previously measured attention shifts (Sperling & Reeves, 1980; Reeves & Sperling, 1986), is slower, has a longer duration, and is effortful.

Sperling, George, and Weichselgartner, Erich. (199x). Episodic theory of the dynamics of spatial attention. *Psychological Review.* (Under revision.)

This paper re-analyzes previous measurements of visual attention in simple reaction-time, choice reaction-time and complex discrimination experiments in which attention was purported to move continuously across space. All these data plus data from attention gating experiments were shown to be quantitatively predicted by a quantal (episodic) theory of spatial attention that proposes instead: (a) visual attention can be resolved into a sequence of discrete attentional acts (episodes); (b) each attentional episode is defined by its spatial facilitation function $f(x,y)$; (c) the transition at time t_0 between episodes is described by a temporal alerting/gating function $G(t-t_0)$; (d) f and G are space-time separable. In support of the theory, new experiments are reported that use a concurrent motor reaction-time task to assess changes in discriminability with distance. When non-attentional factors are corrected for, the duration of an attention shift is independent of the spatial distance traversed and of the presence or absence of interposed visual obstacles. New experiments that test and confirm the theory are reported.

Gegenfurtner, K. and Sperling, G. (1993). Information transfer in iconic memory experiments. Journal of Experimental Psychology: Human Perception and Performance, 1993, 19, 845-866.

This paper investigates the role of selective and nonselective transfer processes in partial reports of information from briefly exposed letter arrays. In order to report letters, viewers must transfer information from a rapidly decaying persistence trace (iconic memory) to a more durable short term memory. At some time following termination of the display, subjects are cued to report a particular row of letters. Transfer that occurs prior to the cue is nonselective; transfer that occurs after the cue is selective. (a) Performance is unaffected by 10:1 variations in the probabilities of short and long cue delays. This implies that viewers use the same transfer strategies at all cue delays. (b) Information transfer that has occurred at various times t before and after the cue is measured by using a post-stimulus mask at time t to eliminate visual persistence. Nonselective and selective information transfer (before and after the cue) are shown to combine additively. (c) Positions within rows differ substantially in their accuracy of report.

A simple model accounts for partial report (cued) performance at different cue delays both with and without a mask, and for whole report (uncued) performance. (1) The time course of iconic legibility after stimulus termination depends on the retinal location (row). (2) Initial attention is directed to the middle row, subsequently it switches to the cue-designated row. (3) The instantaneous location-specific legibility times the instantaneous state of attention, integrated over time, determines cumulative transfer, subject to the capacity limit of durable storage. A review of earlier computational approaches shows that only this model is capable of giving a self-consistent account of information transfer from iconic memory.

George Sperling: HIP Lab Publications, 1991-93

1991 Landy, Michael S., Barbara A. Dosher, George Sperling, and Mark E. Perkins. Kinetic depth effect and optic flow: 2. Fourier and non-Fourier motion. *Vision Research,* 1991, *31,* 859-876.

1991 Parish, David H. and George Sperling, Object spatial frequencies, retinal spatial frequencies, noise, and the efficiency of letter discrimination. Vision Research, 1991, *31,* 1399-1415.

1991 Solomon, Joshua A, and George Sperling. Can we see 2nd-order motion and texture in the periphery? *Investigative Ophthalmology and Visual Science,* ARVO Supplement, 1991, *32, No. 4,* 714. (Abstract)

1991 Werkhoven, Peter, Charles Chubb, and George Sperling. Texture-defined motion is ruled by an activity metric--not by similarity. *Investigative Ophthalmology and Visual Science,* ARVO Supplement, 1991, *32, No. 4,* 829. (Abstract)

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1991 Chubb, Charles, and George Sperling. Texture quilts: Basic tools for studying motion-from-texture. *Journal of Mathematical Psychology,* 1991, *35,* 411-442.

1991 Chubb, Charles, Joshua A. Solomon, and George Sperling. Contrast contrast determines perceived contrast. *Optical Society of America Annual Meeting Technical Digest, 1991,* Vol. 17. Washington D.C.: Optical Society of America, 1991. P. XX. (Abstract)

1991 Sperling, G. and Würst, S. A. (1991). Selective attention to an item is stored as a feature of the item. *Bulletin of the Psychonomic Society,* 1991, *29,* 473. (Abstract)

1992 Shih, Shui-I and George Sperling (1992). Cluster analysis as a tool to discover covert strategies. *Proceedings of the Eastern Psychological Association,* 1992, *63,* 41. (Abstract)

1992 Werkhoven, P., Sperling, G., and Chubb, C. (1992). The dimensionality of motion from texture. *Investigative Ophthalmology and Visual Science,* ARVO Supplement, 1992, *33, No. 4,* 1049. (Abstract)

1992 Werkhoven, P., Sperling, G., and Chubb, C. (1992). *Energy computations in motion and texture. Optical Society of America Annual Meeting Technical Digest, 1992,* Vol. 18. Washington D.C.: Optical Society of America, 1992. P. XX. (Abstract)

1993 Sperling, G. Wurst, S. A., and Lu, Z-L. (1993). Using repetition detection to define and localize the processes of selective attention. In D. E. Meyer and S. Kornblum (Eds.), *Attention and Performance XIV: Attention and Performance XIV: Synergies in Experimental Psychology, Artificial Intelligence, and Cognitive Neuroscience - A Silver Jubilee* Cambridge, MA: MIT Press. Pp. 265-298.

1993 Werkhoven, P., Sperling, G., and Chubb, C. (1993). The dimensionality of texture-defined motion: A single channel theory. Vision Research, 1993, *33,* 463-485.

1993 Solomon, J. A. and Sperling, G. (1993). Fullwave and halfwave rectification in motion perception. *Investigative Ophthalmology and Visual Science,* ARVO Supplement, 1993, , *No. 4,* 976. (Abstract)

1993 Shih, Shui-I and Sperling, G. (1993). Visual search, visual attention, and feature-based stimulus selection. *Investigative Ophthalmology and Visual Science,* ARVO Supplement, 1993, *34, No. 4,* 1288. (Abstract)

1993 Lu, Zhong-Lin and Sperling, G. (1993). 2nd-order illusions: Mach bands, Craik—O'Brien—Cornsweet. *Investigative Ophthalmology and Visual Science,* ARVO Supplement, 1993, *34, No. 4,* 1289. (Abstract)

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1993 Sperling, G. (1993). Spatial, Temporal, and Featural Mechanisms of Visual Attention. *Spatial Vision, 7.* 86. (Abstract)

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1994 Werkhoven, Peter, Sperling, George, and Chubb, Charles. (1994). Perception of apparent motion between dissimilar gratings: Spatiotemporal properties. *Vision Research, 33.* (Accepted for publication, pending revision)

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George Sperling: Talks at Symposia and Meetings of Professional Societies

† Indicates an invited address.
* Indicates an abstract of talk was published.

1991 †George Sperling, Helmholtz Club, University of California, Irvine, February 5, 1991. *Dynamics of Visual Attention: Review and a Theory.*

1991 George Sperling, 87th Meeting of the Society of Experimental Psychologists, University of California at Los Angeles, March 16, 1991. *A Theory of Spatial Attention.*

1991 *Solomon, Joshua A, and George Sperling. Talk presented by Joshua A. Solomon. Association for Research in Vision and Ophthalmology, Sarasota, Florida, April 29, 1991. *Can we see 2nd-order motion and texture in the periphery?*

1991 *Werkhoven, Peter, Charles Chubb, and George Sperling. Poster, presented jointly Association for Research in Vision and Ophthalmology, Sarasota, Florida, April 29, 1991. *Texture-defined motion is ruled by an activity metric--not by similarity.*

1991 *Sutter, Anne, George Sperling and Charles Chubb, Poster, presented jointly Association for Research in Vision and Ophthalmology, Sarasota, Florida, May 1, 1990. *Further measurements of the spatial frequency selectivity of second-order texture meachanisms.*

1991 †George Sperling, Neural Networks for Vision and Image Processing. An International Conference Sponsored by BOston University's Want Institute, Center for Adaptive Systems, Tyngsboro, MA 01879, May 11, 1991. *Two Systems of Visual Processing.*

1991 †George Sperling, Neural and Visual Computation Symposium Center for Neural Sciences New York University, NY, May 31, 1991. *The Spatial, Temporal, and Featural Mechanisms of Visual Attention.*

1991 †George Sperling, National Academy of Sciences, National Research Council, Committee on Vision, Conference of Visual Factors in Electronic Image Communications, Woods Hole, MA, July 23, 1991. *Empirical Observations on Image Compression and Comprehension.*

1991 †George Sperling, The International Society for Psychophysics, Washington Duke Inn, Duke University, Durham, North Carolina, New York University, NY October 19, 1991. *The Featural Mechanism of Visual Attention.*

1991 †*Chubb, C., Solomon, J. A. and Sperling, G. Invited paper presented by Charles Chubb. Optical Society of America, San Jose, California November 7, 1991, *Contrast Contrast Determines Perceived Contrast.*

1991 *George Sperling and Stephen Wurst, Paper presented by George Sperling. Psychonomic Society, San Francisco, California November 22, 1991. *Selective Attention to an Item is Stored as a Feature of the Item.*

1992 *Shui-I Shih and George Sperling. Eastern Psychological Association, Boston, Massachusetts, April 4, 1992. *Cluster Analysis as a Tool to Discover Covert Strategy.*

1992 *Werkhoven, P., Sperling, G., and Chubb, C. Association for Research in Vision and Ophthalmology, Sarasota, Florida, May 6, 1992. *The Dimensionality of Motion From Fexture.*

1992 *Werkhoven, W., Sperling, G., and Chubb, C. Optical Society of America, Albuquerque, New Mexico, September 25, 1992. *Energy Computations in Motion and Texture.*

1992 *George Sperling and Hai-Jung Wu, Paper presented by George Sperling. Psychonomic Society, Saint Louis, Missouri, November 15, 1992. *Defining and Teaching Objectively Accurate Confidence Judgments.*

1993 *†George Sperling, Linking Psychophysics, Neorophysiology, and Computational Vision: A Conference to Celebrate Bela Julesz' 65th Birthday. Rutgers University, New Brunswick, NJ. May 1, 1993. *Spatial, Temporal, and Featural Mechanisms of Visual Attention.*

1993 *Solomon, J. A. and Sperling, G. Talk presented by Joshua A. Solomon. Association for Research in Vision and Ophthalmology, Sarasota, Florida, May 4, 1993. *Fullwave and Halfwave Rectification in Motion Perception.*

1993 *Shih, Shui-I and Sperling, G. Talk presented by Shui-I Shih. Association for Research in Vision and Ophthalmology, Sarasota, Florida, May 6, 1993. *Visual Search, Visual Attention, and Feature-Based Stimulus Selection.*

1993 *Lu, Zhong-Lin and Sperling, G. (1993) Talk presented by Zhong-Lin Lu. Association for Research in Vision and Ophthalmology, Sarasota, Florida, May 6, 1993. *2nd-Order Illusions: Mach bands, Craik—O'Brien—Cornsweet.*

1993 *Chubb, C., Darcy, J. and Sperling, G. Talk presented by Charles Chubb. Association for Research in Vision and Ophthalmology, Sarasota, Florida, May 6, 1993. *Metameric Matches in the Space of Textures Comprised of Small Squares with Jointly Independent Intensities.*

1993 *†Sperling, George and Dosher, Barbara A. Talk presented by George Sperling. Linking Psychophysics, Neurophysiology and Computational Vision. A Conference to Celebrate Bela Julesz' 65th Birthday. Rutgers University, New Brunswick, New Jersey, May 1, 1993. *Structure-from-motion: Algorithms, Illusions, Mechanisms.*

1993 †Sperling, George. Geometric Representation of Perceptual Phenomena. A Conference in Honor of Tarow Indow. University of California, Irvine. July 28, 1993. *The Representation of Motion and Texture.*

1993 †Sperling, George. Society for Mathematical Psychology, Twenty-Sixth Annual Meeting, Norman, Oklahoma. Plenary lecture. August 17, 1993. *Second-Order Perception.*

1993 *†Sperling, George. Ciba Foundation Symposium No: 184. Higher-Order Processing in the Visual System. The Ciba Foundation, 41 Portland Place, London, UK. October 21, 1993. *Full-Wave and Half-Wave Mechanisms in Motion and Texture Perception.*

1993 †Sperling, George. International Workshop on Digital Video for Intelligent Systems. Hosted by Department of Electrical and Computer Engineering, University of California, Irvine, California. December 17, 1993. *An engineering model of human visual processing/Intelligibility of extremely re* duced images.

George Sperling: Invited Lectures at Universities and Institutes

1991 Department of Psychology Colloquium, University of California, Irvine, Irvine, CA, January 10, 1991. *Visual Preprocessing.*

1991 Department of Psychology University of California at San Diego, La Jolla, CA, February 28, 1991. *Mechanisms of Attention.*

1991 University of California, Berkeley Berkeley, California, Joint Cognitive Science Colloquium and Oxyopia Colloquium (Optometry School), March 22, 1991. *Visual Preprocessing.*

1991 University of California, Berkeley Berkeley, California, Department of Psychology/Cognitive Science Colloquium, March 22, 1991. *The Spatial, Temporal, and Featural Mechanisms of Visual Attention.*

1991 Bonny Center for the Neurobiology of Learning and Memory, University of California, Irvine, Irvine, CA, April 8, 1991. *Mechanisms of Visual Attention.*

1991 Salk Institute, University of California at San Diego, La Jolla, CA, April 10, 1991. *Visual Preprocessing.*

1991 Department of Psychology, University of Florida at Gainsville, April 26, 1991. *Systems and Stages of Visual Processing.*

1991 Shanghai Institute of Technical Physics, Shangahi, China, June 17, 1991. *How the Human Visual System Computes Visual Motion* [Host: Prof. Kuang, Ding Bo (Director, SITP); Translators: Dr. Zhang, Ming and Chen, Lulin.]

1991 Department of Computer Science, Shanghai Information-Technology Engineers Examination Center, Fudan University, Shangahi, China, June 18, 1991. *Neural Principles of Preprocessing for Human Pattern Recognition.* [Host: Prof. Wu, Lide (Director, SITEEC).]

1991 Department of Electronic Science and Technology, Institute of Applied Electronics, East China Normal University, Shangahi, China, June 20, 1991. *Measuring Attention* and *How the Human Visual System Computes Visual Motion* [Host: Prof. Weng, Moying (Chairman and Director); Translator: Dr. Zhang, Ming.]

1991 Department of Psychology, Beijing University, and Institute of Psychology, Chinese Academy of Sciences, Beijing, China, June 25, 1991. [Host: Prof. Jing, Qicheng (Director, Institute of Psychology)]
Morning: *The Efficiency of Pereception* [Translators: Dr. Zhang, Ken and Prof. Jing, Qicheng.]
Afternoon: *Measuring Attention.* [Translator: Luo, Chun-Rong.]

1991 Computational Vision Laboratory, Institute of Biophysics, Chinese Academy of Sciences, Beijing, China, June 28, 1991. *First- and Second-Order Motion Perception.* [Host: Prof. Wang Shuo-Rong (Director, Institute of Biophysics); Translator: Prof. Wang, Yun-Jiu (Laboratory Director.]

1991 New York University, Cognitive Sciences Colloquium, September 12, 1991. *Is There Attentional Filtering of Items by Feature as Well as by Location?*

1992 Center for Adaptive Systems Boston University, February 25, 1992. *Is There Attentional Selection of Items by Feature as Well as by Location?*

1992 University of Delaware, Department of Psychology Colloquium, March 4, 1992. *Can Visual Attentional Filter Items by Feature?*

1993 University of California, Irvine, Department of Cognitive Sciences, Vision Lunch Series, January 13, 1993. *2nd-Order Motion Perception.*

1993 University of California, Irvine, Bren Fellows Program, Learned Societies Luncheon, UCI University Club, March 9, 1993. *Modeling Mental Microprocesses.*

1993 University of California, Santa Barbara, First Annual Gottsdanker Memorial Lecture (Department of Psychology). May 27, 1993. *A Theory of Spatial Attention.*

1993 Kenneth Craik Club, University of Cambridge, Cambridge, England, October 25, 1993. *Early Visual Processing.*

1993 University of California, Berkeley. December 3, 1993. *A Theory of Spatial Attention.*