Summary of Research on the Theory of Visual Information

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My research has concerned the theory of information for visual perception.[1] Motivation for studying perceptually acquired information began with the realization that perception is both limited and selective. Understanding acquired information is essential for almost everything else in psychology, from neuroscience to social science, and from receptors to perception, reason, and action. The psychological theory of information encompasses many issues, methods, and applications. My experimental and theoretical research relates to the broad goal of clarifying the nature of information.

The following review is an immodest summary of my research as seen from my perspective. Continuing themes and continuity are emphasized rather than temporally ordered publications or citation indices. From this personal perspective, the assessment is predictably positive and lacking in critical scrutiny. A more objective but less organized survey is the Google Scholar profile: https://scholar.google.com/citations?user=mw5bflQAAAAJ&hl=en.

My interests in experimental psychology began at the University of Cincinnati at about 1960, influenced by William Dember, and motivated by challenges to the then-dominant stimulus-response paradigm that were posed by selective attention. If "stimuli" are defined by the observer's attention, then the causes of behavior were somewhat reversed and demanded new investigation and thinking. Luckily, that scientific interest led me to graduate study with Charles Eriksen at the University of Illinois (1962-'66). Erik was then at an early stage of his research on visual attention, so I benefitted enormously from his creativity as an experimenter, the quality and rigor of his ideas, and his influence as a scientist and person. (See special issue of *Attention, Perception & Psychophysics, 83*, 543, devoted to research inspired by Charles Eriksen. Also: Lappin, J.S., Logan, G.D., Fournier, L.R., & Hoffman, J.E. (2018). Charles "Erik" Eriksen (1923-2018). *Attention, Perception, & Psychophysics, 80* (5), 1030-1034. Kramer, A., Coles, M., Eriksen, B., Garner, W., Hoffman, J., & Lappin, J. (1994). Charles Eriksen: Past, present, and future. *Perception & Psychophysics, 55*, 1-8.)

One noteworthy paper from my graduate research with Erik was **Lappin & Eriksen (1966)** [Use of a delayed signal to stop a visual reaction time response. *Journal of Experimental Psychology*, *72*, 805-811]. We developed a new method for measuring temporal processes. The paradigm, which has had lasting influence, was also subsequently developed and applied by Gordon Logan and in neurophysiology by Jeff Schall (though their interpretations and mine are different). Novel methods of this study included (a) asking participants to respond so rapidly that sometimes they were unable to inhibit a response and

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[1] On the definition of *information*: Information is defined by corresponding structural variations in physically separate systems. Information is not objectively definable. Rather, it is created by transmission, by correlated variations — between sender and receiver; between input and output; between environment, sensory receptors, neural systems, perception, memory, decisions, and actions. In the case of perception, the corresponding variations are often spatiotemporal, not fundamentally statistical. Perception, attention, and cognition in general can be regarded as processes for creating information — by recognizing or establishing corresponding relational structures in multiple domains. Concepts of information were discussed in more detail recently by **Lappin & Bell (2021)** [Form and function in in information for visual perception. *iPerception, 12* (6), 1-22 (Special Issue: The ecological approach of James J. Gibson: 40 years later)].

(b) evaluating the response inhibition probability as a function of the RT and the stop-signal delay. The finding that response control by stimulus information depended jointly on RT and time after the go-signal, was also found in studies that measured the dependence of response accuracy on RT — e.g., **Lappin & Disch (1972)** [The latency operating characteristic: I. Effects of stimulus probability on choice reaction time. *Journal of Experimental Psychology*, *92*, 419-417] and **Harm & Lappin (1973)** [Probability, compatibility, speed and accuracy. *Journal of Experimental Psychology*, *100*, 416-418]. Both studies found that response accuracy increased linearly with RT, invariant with changes in average RTs produced by changes in stimulus probability.

Converging evidence about how behavioral control depends on RT has emerged from recent studies of RT hazard rates (response rates conditioned on time) in factorial experiments. Stimulus and task conditions were found to influence the relative response rates (in bits/s) at any given RT, invariant with the other effects on RT distributions: **Lappin, Morse, & Seiffert (2016)** [The channel capacity of visual awareness divided among multiple moving objects. *Attention, Perception, & Psychophysics, 78*, 2469-2493] and **Lappin, Seiffert, & Bell (2020)** [A limiting capacity of visual perception: Spreading attention divides the rates of perceptual processes. *Attention, Perception, & Psychophysics, 82,* 2652-2672.]. Our results support a *variable rate theory of RT* — an alternative to the standard theory that RTs represent process completion times. Response rates at any given RT were found to involve the synchronous influence of multiple independent processes of perception and action. Moreover, response rates at any given time were divided by the attentional set size of the visual field, invariant with RT and independent of the effects of other variables. The conscious awareness of visual targets occurred at a limited rate (measurable in bits/s) that was divided by the spread of attention. That hypothesis and efforts to find its correlates in brain activity are ongoing concerns of my current research.

Another product of my graduate research was my Ph.D thesis, **Lappin (1967)** [Attention in the identification of stimuli in complex visual displays. *Journal of Experimental Psychology*, *75*, 321-328]. This study evaluated how attention to one dimension (size, color, or shape) affected identifications of other dimensions of the same or different objects. In each condition, the observer's task was to identify three designated features in complex displays of nine three-feature objects. The results were early evidence of object-based attention: Responses were substantially more correct for three features of the same object, as compared to those for features of three separate objects. And identifications of the same feature dimension of three objects were much easier than identifications of different features of three objects. Thus, the perception of multiple features depended strongly on their configuration, as parts of the same vs different objects or values of the same vs different features. Another surprising finding, however, was that *within* each of these configuration conditions, accuracies of the three responses were always independent. The perception of one feature was unaffected by the perceptions of other features — despite the large *between-condition* effects on perceptions of multiple features. That is, perceptual organizational was shaped by the demands of the task.

Much of my subsequent research was directed at the idea that visual information is based on spatial and temporal *relationships*, involving both geometric and statistical relations. **Lappin & Bell (1972)** [Perceptual differentiation of sequential visual patterns. *Perception & Psychophysics*, *12*, 129-134] showed that visual information is not necessarily temporally integrative: Spatiotemporal image changes are visually salient. **Lappin, Bell, Harm, & Kottas (1975)** [On the relation between time and space in the visual discrimination of velocity. *Journal of Experimental Psychology: Human Perception and Performance*, *1*(4), 383-394] showed that motion is a fundamental perceptual property not derived from elementary discriminations of space and time. **Bell & Lappin (1973)** [Sufficient conditions for the discrimination of motion. *Perception and Psychophysics*, *14*, 45-50] and **Lappin & Bell (1976)** [The detection of coherence in moving visual patterns. *Vision Research*, *16*, 161-168] were well-known early demonstrations of sensitivity to statistically coherent spatiotemporal structure defined by relations between just two brief random-element patterns. Importantly, vision is sensitive to the spatiotemporal structure of not only translations, but also rotations, expansions, shear, and combinations thereof: **Bell & Lappin (1979)** [The detection of rotation in random-dot patterns. *Perception & Psychophysics*, *26*, 415-417], **Lappin, Norman, & Mowafy (1991)** [The detectability of geometric structure in rapidly changing optical patterns. *Perception*, *20*, 513-528]. Such performance is characteristic of linear systems, where output reflects the structure of input— e.g., **Lappin & Kottas (1981)** [The perceptual coherence of dynamic visual patterns. *Acta Psychologica*, *48*, 163-174].

Research on the perception of spatiotemporal organization led to research on the perception of *3D structure and motion*. **Lappin, Doner, & Kottas (1980)** [Minimal conditions for the visual detection of structure and motion in three dimensions. *Science*, *209*, 717-719] demonstrated that vision is sensitive to 3D structure and motion defined by only two successive frames of randomly positioned dots. Evidence about this phenomenon was extended by and **Doner, Lappin, & Perfetto (1984)** [The detection of 3-dimensional structure in moving optical patterns. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 1-11].

A key idea that emerged from research on perceiving structure from motion was that *surface structure* is a fundamental form of visual information. Basic studies included **Norman & Lappin (1992)** [The detection of surface curvatures defined by optical motion. *Perception & Psychophysics*, *51*, 386-396], **Lappin, Craft, Ahlström, & Tschantz (1995)** [Spatial primitives for seeing 3D shape from motion. T. Papathomas, C. Chubb, A. Gorea, & E. Kowler (Eds.) *Early vision and beyond*. Cambridge: MIT Press. Pp. 145-153], **Perotti, Todd, Lappin, & Phillips (1998)** [The perception of surface curvature from optical motion. *Perception & Psychophysics*, *60* (3), 377-388], and most importantly, **Lappin & Craft (2000)** [Foundations of spatial vision: From retinal images to perceived shapes. *Psychological Review*, *107* (1), 6-38]. The essential role of surface structure was also found in studies of stereoscopic vision: **Norman, Lappin, & Zucker (1991)** [The discriminability of smooth stereoscopic surfaces. *Perception*, *20*, 789-807], **Lappin & Craft (1997)** [Definition and detection of binocular disparity. *Vision Research*, *37* (21), 2953-2974], **Lappin & Craft (2000)**, **Lappin, Norman, & Phillips (2011)** [Fechner, information, and shape perception. *Attention, Perception, & Psychophysics*, *73*, 2353-2378], and **Lappin (2014)** [What is binocular disparity? *Frontiers in Psychology, Perception Research, http://journal.frontiersin.org/Journal/10.3389/fpsyg.2014.00870/full*].

Measurement has been a frequent methodological emphasis. My experiments are often designed to evaluate (a) the *precision* of observers' discriminations of optical properties and (b) the *invariance* of that precision under transformations of the optical images, observational conditions, context, and responses. The logic and importance of these measurement criteria are discussed by **Lappin (2016)** [Identifying spatiotemporal information. In J.W. Houpt & L.M. Blaha (Eds.) *Mathematical Models of Cognition and Perception, Vol I: A Festschrift for James T. Townsend.* Ch. 7, pp. 107-151.) New York: Routledge]. The precision of visual discriminations guides inferences about the neural mechanisms that can maintain reliability and resolution from retinal input to behavioral output. The associated invariance criteria are necessary for Identifying the specific properties that constitute visual information. These methods are illustrated by the *Psychological Review* study of **Lappin & Craft (2000).** A related application of invariance criteria in studies of response time is a basis for identifying causal factors and component processes in response times — as in the recent study of **Lappin, Seiffert, & Bell (2020)** [cited above]**.**

The fact that certain visual discriminations exhibit remarkable precision and invariance was documented by **Lappin & Craft (1997, 2000)**. Specifically, vision exhibits "*hyperacuity*" — better than the optical limits associated with diffraction and photoreceptor density — for differences in 3D surface structure conveyed by either differential motion or stereoscopic disparities. Hyperacuities for detecting phase relations among separate moving features were also quantified by **Lappin, Donnelly, & Kojima (2001)** [Coherence of early motion signals. *Vision Research*, *41*, 1631-1644], and **Lappin, Tadin, & Whittier (2002)** [Visual coherence of moving and stationary image changes. *Vision Research*, *42*, 1523-1534]. A recent review by **Lappin & Bell (2023)** [The coherent organization of dynamic visual images. *Frontiers in Computer Science, 5*: 1124230. (Research topic: Perceptual organization in biological and computer vision.], shows that these hyperacuities for the structure and motion of dynamic images imply that (a) spatial positions and relations are defined by the optical images rather than retinal anatomy, (b) moving images produce coherent visual signals, and (c) the visual system maintains coherent phase structure from retina to cortex. Importantly, theoretical research by Koenderink & van Doorn, identified an isomorphism between spatiotemporal structure of dynamic images and the structure and motion of environmental surfaces. **Lappin & Craft (2000), Lappin, Norman, & Phillips (2011), Lappin (2014, 2016),** and **Lappin & Bell (2021, 2023)** review extensive experimental evidence for this isomorphism between environmental surface structure and perception.

Precise spatial discriminations also demonstrated that in certain conditions vision can derive *metric spatial relations from invariance under motion*: **Lappin & Fuqua (1983)** [Accurate visual measurement of three-dimensional moving patterns. *Science*, *221*, 480-482], **Lappin & Love (1992)** [Planar motion permits perception of metric structure in stereopsis. *Perception & Psychophysics*, *51*, 86-102], and **Lappin & Ahlström (1994)** [On the scaling of visual space from motion—In response to Pizlo and Salach-Golyska. *Perception & Psychophysics*, *55*, 235-242].

Comparative evaluations of precision in discriminating various spatial relations have also provided insights about *space perception in natural environments*, involving relations of relative length, collinearity, and exocentric direction — e.g., **Norman, Lappin, & Norman (2000)** [The perception of length on curved and flat surfaces. *Perception & Psychophysics*, *62* (6), 1133-1145], **Koenderink, van Doorn, & Lappin (2000)** [Direct measurement of the curvature of visual space. *Perception*, *29*, 69-79], **Koenderink, van Doorn, Kappers, & Lappin (2002)** [Large-scale visual frontoparallels under full-cue conditions. *Perception*, *31*, 1467-1475], **Koenderink, van Doorn, & Lappin (2003)** [Exocentric pointing to opposite targets. *Acta Psychologica*, *112*, 71-87], **Norman, Norman, Lee, Stockton, & Lappin, (2004)** [The visual perception of length along intrinsically curved surfaces. *Perception & Psychophysics,* 66 *(1), 77-88*], and **Lappin, Shelton, & Rieser (2006)** [Environmental context influences visually perceived distance. *Perception & Psychophysics*, *68* (4), 571-581].

The importance of temporal thresholds for identifying what the eye sees best is also illustrated by an influential research program developed by Duje Tadin. The first of many papers by Tadin and colleagues was **Tadin, Lappin, Gilroy, & Blake (2003)** [Perceptual consequences of centre-surround antagonism in visual motion processing. *Nature*, *424*, 312-315], who discovered and described the antagonistic center-surround organization of visual motion mechanisms, along with some of its perceptual consequences. One counter-intuitive effect is that motion directions of high-contrast patterns become more difficult with increasing size. This and many other studies by Tadin and colleagues (including **Tadin & Lappin (2005)** [Optimal size for perceiving motion decreases with contrast. *Vision Research*, *45*, 2059-2064], **Tadin, Lappin, & Blake (2006)** [Fine temporal properties of center-surround interactions in motion processing revealed by reverse correlation. *The Journal of Neuroscience*, *26*, 2614-2622]) and **Tadin, Paffen, Blake, & Lappin (2008)** [Contextual modulations of center-surround interactions in motion revealed with the motion aftereffect. *Journal of Vision*, *8*(7):9, 1-11] led to new physiological evidence about receptive fields in cortical area MT, as well as new evidence about the effects of aging and schizophrenia on this neural organization (e.g., **Tadin, Kim, Doop, Gibson, Lappin, Blake, & Park (2006)** [Weakened center-surround interactions in motion processing in schizophrenia. *The Journal of Neuroscience, 26*, 11403-11412]). An important recent study combines converging correlational and causal evidence to show that this basic neural mechanism underlies figure-ground segmentation and the complementary visual functions of spatial differentiation and integration of image motion — **Tadin, Park, Dieter, Melnick, Lappin, & Blake (2019)** [Spatial suppression promotes rapid figure-ground segmentation of moving objects. *Nature Communications, 10*, Article 2732. https://doi.org/10.1038/s41467-019-10653-8].

Temporal thresholds for motion discrimination were also critical in the study of **Lappin, Tadin, Nyquist, & Corn (2009)** [Spatial and temporal limits of motion perception across variations in speed, eccentricity, and low vision. *Journal of Vision, 9*(1): 30, 1-14], which showed that visual resolution of motion is similar in both retinal fovea and periphery, despite large central-peripheral differences in cellular densities and spatial acuity for stationary images. **Borghuis, Tadin, Lankheet, Lappin, & van de Grind (2019)** [Temporal limits of visual motion processing: Psychophysics and neurophysiology. *Vision*, *3*(1), 5] recently reported converging physiological and behavioral evidence that behavioral motion discriminations and ganglion cell spike trains have similar temporal resolution of image motion. As noted by **Lappin & Bell (2023)** [cited above], this physiological evidence is consistent with psychophysical evidence that the visual system conserves the coherence of spatiotemporal phase structure from retina to cortex. A promising area of research concerns the hypothesis that neural information is created and organized by the spatiotemporal phase structure of neural activity.

Beyond the optical properties of specific patterns, visual discrimination and recognition also depend on an observer's *prior knowledge*. Indeed, this non-objective statistical aspect of visual information is counter-intuitive and sometimes overlooked in studying cognitive information processing. **Lappin & Uttal (1976)** [Does prior knowledge facilitate the detection of visual targets in random noise? *Perception and*

Psychophysics, *20*, 367-374] found that the set size of potential targets had substantial effects on even forced-choice detections. These effects, however, were predicted by Luce's (1959, 1963) Choice Theory, and are attributable to the input information rather than the cognitive processing of that information. Subsequent investigations also found that other behavioral effects of prior knowledge also did not involve perceptual processing per se when statistical and psychophysical factors were properly controlled — **Lappin (1978)** [The relativity of choice behavior and the effect of prior knowledge on the speed and accuracy of recognition. In N.J. Castellan, Jr., and F. Restle (Eds.), *Cognitive theory, Vol. 3*. Hillsdale, N. J.: Lawrence Erlbaum], **Staller & Lappin (1979)** [Word and nonword superiority effects in a letter detection task. *Perception and Psychophysics*, *25*, 47-54], **Staller, Lappin, & Fox (1980)** [Stimulus uncertainty does not impair stereopsis. *Perception and Psychophysics*, *27*, 361-367], and **Lappin & Staller (1981)** [Prior knowledge does not facilitate the perceptual organization of dynamic random-dot patterns. *Perception and Psychophysics*, *29*, 445-456].

Nevertheless, other experiments have shown clearly that *familiarity and meaning* facilitate perceptual organization and pattern recognition. The facilitating role of linguistic knowledge in particular has been well documented for recognizing patterns of multiple letters — e.g., **Lappin & Lowe (1969)** [Meaningfulness and pronounceability in the coding of visually presented verbal materials. *Journal of Experimental Psychology*, *81*, 22-28], **Singer, Lappin, & Moore (1975)** [Interference of various word parts on color naming in the Stroop test. *Perception & Psychophysics*, *18*, 191-193], **Staller, Buchanan, Singer, & Lappin (1978)** [Alexia without agraphia: An experimental case study. *Brain and Language*, *5*, 378-387], and **Staller & Lappin (1981)** [Visual detection of multi-letter patterns. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 1258-1272]. The latter study investigated how detection of multi-letter targets in rapid series of similar patterns (a) compares with detection of the component letters and (b) is influenced by familiarity with particular sequences. One noteworthy finding was that two-letter patterns were detected more accurately than their one-letter components. This advantage reflects the benefit of increased complexity in discriminating between target and nontarget patterns. Evidence about the facilitative effects of prior experience has now come from studies of reading and of expertise in face and object recognition, but such effects were less understood at the time of our experiments.

A striking example of *cognitive influence on perceptual organization* of optical patterns was found by **Tadin, Lappin, Blake, & Grossman (2002)** [What constitutes an efficient reference frame for vision? *Nature Neuroscience*, *5*, 110-1115]. We evaluated discriminations of coherent phase oscillations of multiple local patches arranged in various patterns either with or without a recognizable global organization. For example, patterns in one condition were biological motion images of either upright or inverted point-light walkers, in which 10 moving Gabor patches were substituted for points of light at moving joints. Coherent phase oscillations of the component elements in these and other patterns were always more visible in patterns with recognizable global form (e.g., upright walkers) than in similar patterns without such organization (e.g., inverted walkers). Thus, the reference frame for seeing temporal correlations among changing local features is the perceived global form rather than local image motions or features.

If experience can facilitate perceptual organization, then some perceptual deficits that occur in low vision, for example, might be ameliorated by *training*. **Nyquist, Lappin, Zhang, & Tadin (2016)**

[Perceptual training yields rapid improvements in visually impaired youth. *Scientific Reports, 6*, 34731-34742] recently investigated this possibility in research on peripheral vision, which is often underutilized in young persons with low acuity. Training of only about 8 hours in an attentionally demanding motion tracking task combined with a spatially and temporally unpredictable motion discrimination task produced significant improvements in visual performance on a variety of visual performance tests — improvements greater than those from either an action video game or a control video game. Training effects were generally larger in the far periphery, and appeared to persist 12 months after training. The training benefits likely derived from sustained attention to multiple dynamic targets while concurrently trying to detect unpredictable events.

Recent and current research has aimed to measure *the rate of conscious visual perception*. Two recent studies evaluated response time hazard rates for detecting target events in ongoing patterns of visually monitored moving objects — **Lappin, Morse, & Seiffert (2016)** and **Lappin, Seiffert, & Bell (2020)** [cited above]. The results of both studies indicated that conscious perception occurs at a measurable limited rate. Our working hypothesis is a version of Shannon's (1948) Fundamental Theorem — that information transmission over any given channel cannot exceed some energy-limited maximum rate, regardless of how the information is encoded. We found that when observers attended to multiple independently moving objects, their speed in perceiving any given target event was reduced in proportion to the number of attended objects. The set size of attention and the temporal processes of visual signal acquisition and response selection all exerted continuous independent parallel influence on perceptual *rates*; and attentional set size had a divisive effect on conditional response rates, invariant with RT. Lappin, Seiffert, & Bell generalized the previous findings by Lappin et al. (2016) and added new methods, new results, and a new theoretical picture of the limited capacity of visual awareness. In addition to its many potential applications, this method of measuring perceptual capacity may offer an opportunity to link the rate of conscious perception & performance with the brain's energy-limited rate of entropy. An aim of this developing collaborative research (with Prof. Catie Chang in Vanderbilt's School of Engineering) is to link rates of behaviorally measured conscious awareness to physiological measures of neural activity, using EEG and fMRI.

Obviously, the research described above is not really "mine". It has been built on the substantial efforts and insights of many talented colleagues with whom I have been lucky to collaborate and learn. In addition to the influence of my early mentors, William Dember, Harry Hake, and especially Charles Eriksen, I have been privileged to benefit from collaborations with many talented graduate students and post-docs, including Bart Anderson, Herb Bell, Randolph Blake, Bart Borghuis (student of Wim van de Grind), Warren Craft, Jon Doner, Michele Falzett, O. J. Harm, Brian Kottas, Doug Morse, Lyn Mowafy, Farley Norman, Jeff Nyquist, Marty Singer, Josh Staller, and Duje Tadin. My research efforts have also substantially benefitted by interactions and collaborations with many other friends and colleagues, including Herb Bell, Randolph Blake, Catie Chang, John Compton, Emerson Foulke, Lisa Fournier, Bob Fox, Richard Haglund, Bela Julesz, Jan Koenderink, Gordon Logan, Farley Norman, Flip Phillips, John Rieser, Brian Rogers, Jeff Schall, Adriane Seiffert, Marty Singer, Mike Templeton, James Todd, James Townsend, Bill Uttal, Andrea van Doorn, Wim van de Grind, Bill Warren, and Tom Wasson. The influence of these and others is too extensive to describe and much more than suggested by co-authorships.