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The evolution of explanations of a perceptual phenomenon: A case history using the Ternus effect

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Abstract. The Ternus effect involves a multi-element stimulus that can lead to either of two different percepts of apparent movement depending upon a variety of stimulus conditions. Since Ternus's 1926 discussion of this phenomenon, many researchers have attempted to explain it. We examine the history of explanations of the Ternus effect and show that they have evolved to contemporary theoretical positions that are very similar to Ternus's own ideas. Additionally, we describe a new experiment showing that theoretical positions that emphasize element grouping and element identity within groups can predict the effects of certain stimulus manipulations on the Ternus effect.

1 Introduction and purpose

Traditionally, one of the nominal goals of psychology has been to provide explanations for the phenomena it studies. What is meant by 'explanation' is not always clear, but there does appear to be some consensus, particularly since the decline of Skinnerian behaviorism, that an explanation should contain constructs (or explanatory mechanisms) that go beyond a superficial description of the observable relationship between manipulated variables and subsequent behavior. To the extent that explanatory mechanisms have a physical basis, or can be otherwise objectified, the explanations that use them should be relatively stable and long-lived. For example, human color-matching phenomena were explained early on by the theoretical existence of three visual pigments possessing broad absorption spectra while having different peak sensitivities. The theoretical pigments were later discovered and objectified and, with the exception of some minor adjustments and extensions, the explanation has been stable for at least 150 years (cf Boring 1942).

On the other hand, explanations consisting of, or at least potentially employing, purely hypothetical constructs appear to be somewhat less stable and long-lived. Thus, for example, models of memory that incorporate theoretical mechanisms have evolved over time and continue to change. The purpose of this paper is to trace historical explanations of a single perceptual phenomenon and to uncover the kinds of evolutionary change 'explanation' of this phenomenon has undergone.

The phenomenon we consider here is the relatively well-known 'Ternus phenomenon' (Ternus 1926/1938), based upon the earlier work of Pikler (1917). As will be described in more detail below, the Ternus phenomenon occurs in its most exemplary form with a fairly simple and straightforward apparent-movement display consisting of three elements arranged horizontally on each of two stimulus frames, often presented along with interstimulus interval (ISI) frames (see figure 1). The first frame of the display contains three elements (eg dots, squares, bars) equally spaced in the horizontal dimension. The second frame contains the same three elements displaced laterally by the distance separating neighboring elements, such that the positions of two of the original elements are now occupied by two different elements. To produce the illusion of apparent movement, the two stimulus frames are alternated at brief stimulus durations (eg 200 ms), frequently with dark or gray homogeneous ISIs between them.

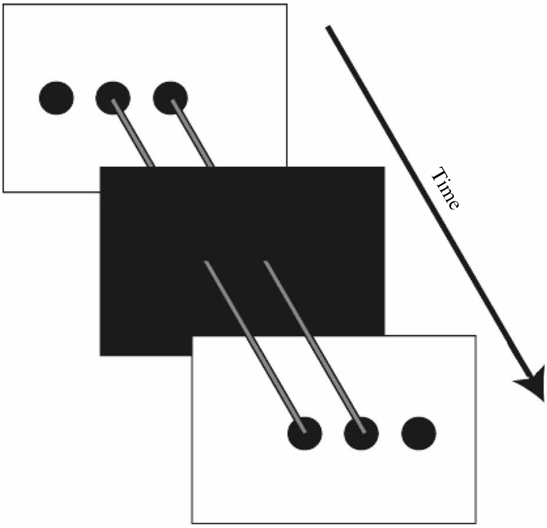

Figure 1. Graphic representation of the presentation of the 'standard' Ternus display over time. Each rectangle represents one frame of the display. Note that the gray 'connecting lines' are shown to help the reader locate Ternus elements that appear in corresponding locations across frames; no such marks are typically presented in an experiment. Note that in actual experimental uses of the display, the second stimulus frame is usually followed by another ISI frame, and then the entire sequence is repeated a number of times.

Numerous studies (summarized by Petersik 1989, 1994) have shown that short ISIs lead to a percept of stationary 'central' elements with a single 'outside' element moving from end to end (hence the name 'element movement'). However, longer ISIs lead to a percept in which all three elements shift back and forth together as a group (hence the name 'group movement'). Intermediate ISIs yield different percentages of element and group movement, depending upon their exact values. Additionally, at some intermediate ISI (whose value depends upon the observer), steady viewing of the alternating frames leads to a bistable percept, ie periodic changeovers from one percept to the other, but never both simultaneously. Dawson and Wright (1994) have argued that a third percept—simultaneity—exists when very short frame durations and ISIs are used; however, this can be considered as a percept existing outside the temporal resolution of the motion-perception system, as described at least as early as 1912 by Wertheimer. As such, it is not a percept that is particularly unique to the Ternus display.

The Ternus phenomenon makes an interesting case study of theoretical explanations for several reasons. First, as mentioned above, it is simple and easily replicated; subsequently, there have been many studies regarding it. Second, the percepts associated with it are relatively exclusive; that is, observers usually report one or the other, but never the two simultaneously and only occasionally some other percept. Third, from its earliest reports until the present, this phenomenon has had no lack of theoretical explanations. Finally, several authors who have made theoretical contributions to our understanding of the Ternus effect are still living and may be able to comment on the perspectives we provide.

In the following section of this paper we consider mainly explanations that attempt to account for the Ternus phenomenon in particular. We do not consider more general approaches to motion perception unless they have had some significant impact upon the way authors have approached the Ternus effect. Additionally, we consider important empirical studies that, in the absence of suggested explanations, have had an impact on the interpretation of the Ternus phenomenon. We have attempted to be comprehensive in our citation of theoretical and related empirical contributions, although we are aware of the likelihood that we have overlooked some sources. We do not try to provide details of research methodology or even theory; those are available in the primary sources. Rather, our outlook is on historical development. We have tried to be selective in examining primarily papers that appear to have had a strong impact on the evolution of explanation of this effect.

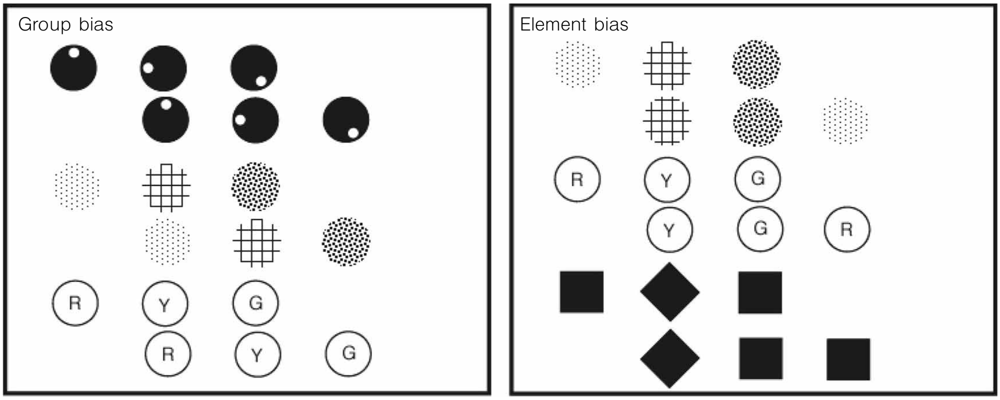

Figure 2. Examples of the stimuli used to create group- and element-movement biases in our unpublished research. For each collection of Ternus elements, the upper row represents the stimuli and positions in which they appeared in one stimulus frame while the bottom row represents the stimuli and positions of the second frame. Empirically, the stimuli labeled 'Group bias' and 'Element bias' each produced significant shifts of subject responses in the predicted direction (relative to control stimuli).

2 Evolution of explanations

It may be unsurprising to see that explanations of the Ternus effect evolved in tandem with the changing Zeitgeist. We do not have information about how the person to whom Ternus attributed discovery of his display (ie Pikler 1917) explained it. However, in an internet review of the history of Hungarian psychology, Pléh (1997) characterized Pikler's theoretical position as follows:

> "... [He] made a serious contribution to the issues regarding the basic units and events of mental life. His synthetising [sic] work (Pikler 1917) tries to promote the principle of negation in sensation as a result of the active components of perception. It was intended to be a notion that would subsume all the already known 'counterphenomena' in perceptual organization such as contrasts, after images and so on." (page 5)

Ternus, a Gestaltist, manipulated his displays in ways that would shed light upon grouping effects. He emphasized the overall organization of elements and whether individual elements maintained their relative role in the group across frames: If the role of individual elements in the group was maintained across frames, group movement would be favored; otherwise element movement occurred. As the explanatory power of the Gestalt movement declined, so did published explanations of the Ternus phenomenon.

2.1 *Origins: Phenomenal identity and Gestalt psychology*

The display shown in figure 1 is based on only one of several similar examples provided by Ternus (1926/1938). Ternus was concerned with what today we might call 'the correspondence problem' (eg Ullman 1979) or the question how the visual system determines which points in one image correspond with their partners in another, different, image. Ternus did not report such things as frame duration and ISI, but he did suggest that, with a few exceptions attributable to unusual attention, fixation, or problems with the "surveyability" of the stimuli (by which he seems to have meant the ability to see, or 'take in' all stimulus elements at once), observers tended to see group movement ('identity exchange' in his words) in the figure 1 type of display.

As a Gestaltist, Ternus argued that the "phenomenal identity" of elements in his displays rests upon the "meaning or role which the [part] has in the two figures ... . Phenomenal identity depends upon Gestalt identity; homologous parts in two Gestalten will exhibit phenomenal identity; phenomenal identity is a characteristic not of piecewise relationships but of whole-phenomena" (page 154). Thus, it seems clear that Ternus believed observers of his display would first identify meaningful groups in each of the frames of his display, and then perceive movement in terms of the displacements of the groups. More recently, the idea that meaningful groups of elements are identified in individual stimulus frames has been called "spatial grouping effects" by Kramer and Yantis (1997) and "within-frame grouping" by He and Ooi (1999).

On the basis of this kind of explanation, any factor that makes it more difficult to perceive a meaningful group of elements in either frame of the display should reduce the tendency to see group movement and correspondingly enhance element movement. Indeed, Ternus showed displays in which the 'overlapping' elements of successive frames were offset (relative to the non-overlapping ones) or otherwise emphasized, leading to reports of their remaining stationary (ie a lack of group movement). In such cases, instead of seeing a unitary moving whole, the observer sees a 'duality', or at least one moving figure and one stationary figure.

Thus, if an explanatory mechanism existed in Ternus's account, it would have to be the tendency on the part of an observer to organize elements into meaningful groups. Logically, this 'grouping' seems to have been thought of as preceding motion analysis itself. To the extent that meaningful groups can be found in successive frames, observers will perceive unitary group movement in the type of displays described by Ternus.

To the best of our knowledge, few studies (at least few English-language studies) between 1926 and about 1974 referred directly to Ternus's work and, of them, none offered new theoretical interpretations. Wallach (1935/1996) mentioned Ternus only in a footnote. Metzger (1936) reproduced some of Ternus's demonstrations and used them in support of what he called the "law of least change", namely "... whenever possible, perceived movement takes place in a way that preserves the shape of the moving object" (page 3). As was the case with Ternus's position, this implies that shape or form is necessarily processed before motion. In an effort to elucidate the relationship between groups and the individuals that compose them, the social psychologist Solomon Asch (1952) made reference to the Ternus phenomenon. He showed the 'standard' Ternus display, described the basic findings, and interpreted them much as Ternus had. Similarly, brief mention of Ternus's displays had been made in books by Bozzi (1939/1969) and Guillaume (1937).

Kolers (1972) also referred to Ternus's work and theoretical position. However, on the basis of his own studies of apparent-movement phenomena, Kolers rejected the notion that form processing precedes motion processing. Instead, he suggested that form is merely a (relatively weak) factor in determining the nature of apparent movement. Kolers was among the first to suggest that motion analysis involves two systems:

> "A visual stimulus that falls on the eye may be thought to generate two signals. One is a spread of excitation throughout the nerve fibers in the retina itself, which will be called the Horizontal signal. The other is a message to deeper parts of the nervous system, which will be called the Vertical signal. The Horizontal or H-signal is ideally suited to represent information about the location of a stimulus. The Vertical or V-signal is equally well-suited to represent information about identity." (pages 71 – 72)

Although he was not explicit in stating so, for Kolers it would seem that the existence of element movement and group movement depends upon the arrival times of H- and V-signals, with H-signals (producing element movement) dominating at lower alternation rates because of their lower-level, hard-wired status.

2.2 *Bistability as competition between motion processes*

As shown below, the duality of the perceptual experience associated with the Ternus effect found a ready explanation in the two-process distinction as physiologists began to explore X- and Y-cells in the visual system and psychophysicists began to define 'sustained' and 'transient' channels. Thus, in the mid-1970s interest in explaining the percepts of the Ternus display was reborn. A natural extension of this line of thinking involved the development of the visible-persistence hypothesis, since persistence was also being related to the sustained/transient dichotomy (eg Breitmeyer 1984).

Perhaps because of the changes in research emphases and funding associated with World War II and its antecedents, followed by the emergence of a dominant behaviorism in psychology, few references to Ternus's work other than translations appeared between 1926 and 1974, when Kaufman (1974) published his text, *Sight and Mind*. Kaufman described Ternus's basic stimulus, and used the findings to argue against the idea that 'velocity detectors' can be used to explain all instances of perceived motion.

After reading of Ternus's work in *Sight and Mind*, researchers in Alan Pantle's laboratory at Miami University began investigating his display tachistoscopically and found that initially they could not produce the same group-movement types of percepts that Ternus had claimed predominated. However, experimentation quickly showed that the appearance of either group or element movement depended critically upon the rate at which frames alternated. These researchers were struck by several aspects of this bistable display. (i) Unlike other forms of bistability (eg the Necker cube), the percepts associated with the Ternus display were controllable by the experimenter with some predictability; ie stimulus factors had a strong influence on the movement reported by most subjects. (ii) The movement percepts were quite distinct and mutually exclusive: No one ever reported them together at the same time, or reported a mixture of the two. (iii) Each of the percepts could be selectively adapted so that, following the period of adaptation, subjects would be more likely to report the alternative percept than when in an unadapted state (Petersik and Pantle 1979). Furthermore, Pantle and Picciano (1976) showed that either dichoptic presentation of the Ternus stimulus frames or contrast reversal of the stimuli (ie black dots on white background in one frame alternating with white dots on black background in the other) nearly completely eliminated the element-movement percept at any ISI.

Given the three observations above, Pantle and Picciano (1976) and Petersik and Pantle (1979) were drawn to the hypothesis that each motion percept was associated with a different underlying motion-processing system (or subsystem). The fact that dichoptic viewing eliminated element movement entirely suggested forcefully that element movement relied on processing at early levels of the visual system (ie prior to the cortical level at which the inputs from the two eyes are combined). On the other hand, the fact that group movement existed under dichoptic viewing suggested that it occurred at a relatively late, higher, level of processing.

Initially, Petersik and Pantle developed hypothetical motion processes that were alleged to produce the two motion percepts. These were the lower-level 'ε-process' and higher-level 'γ-process', producing element movement and group movement respectively. The two processes were envisioned as being in competition for further processing and ultimate representation in consciousness, and spontaneous alternations between element and group movement were thought to reflect such competition (cf Attneave 1971).

Somewhat before researchers in Pantle's laboratory were drawing conclusions about the movements seen with the Ternus display, Braddick (1973, 1974) studied the perceptual segregation of correlated, displaced areas in random-dot kinematograms (RDKs) to develop the notions of 'short-range' and 'long-range' processes in human motion perception, each of which was thought to detect motion under different spatial and temporal ranges and was subject to different stimulus limitations. Because many of the stimulus conditions that influenced the relative dominance of group and element movement were the same as those influencing the ability to segregate correlated areas in RDK frames, Petersik and Pantle (1979) identified their ε-process with Braddick's 'short-range' process and their γ-process with the 'long-range' process in apparent movement.

In passing, the authors also related the ε-process and γ-process to the psychophysical 'sustained' and 'transient' visual channels that were emerging in the literature (eg Breitmeyer and Ganz 1976; Tolhurst 1975). Later, Pantle and Petersik (1980) added more empirical correlations between the ε-process/γ-process distinction and the sustained-/transient-channel distinction based upon their studies of the Ternus display. The properties associated with the putative motion systems and their apparent relationships to other theoretical constructs were later summarized by Petersik (1989).

Because mutual support was arising from studies using different stimuli (eg RDK displays and the Ternus display), the two-process distinction in motion perception gained some ground as the decade of the 80s began. However, it soon became clear that the explanation of element movement in the Ternus display needed refinement. Braddick and Adlard (1978) were the first to point out that both the motion of the 'outer' dot in element movement and the lack of movement of the inner, overlapping dots needed explanation. Their research led them to suggest that the 'short-range' process actually generated a null signal (ie a 'no-movement' signal) with respect to the overlapping dots when stimulus conditions favored element movement. At the same time, the long-range process was thought to be responsible for the motion of the outer dot. As the authors put it:

> "... if the low-level process—hypothetically, activity of directional detectors quite early in the visual pathway—is signaling that the inner two [overlapping] lines are stationary, that information constrains the interpretation that the higher-level process can select. If the inner elements have to be seen as stationary, then the third element must be seen to move between the outer two positions."[(1)] (pages 424–425)

Petersik (1989) later suggested that the 'null-movement detection' of the short-range process, coupled with its sensitivity for small, local movements, would allow an observer to simultaneously detect small movements in an object or its parts while maintaining an overall percept that the object is not undergoing a large position change. In any case, the need to explain the stationary appearance of the overlapping elements during element movement led to other developments in explanations of the Ternus effect.

While tacitly accepting the principle that two separate perceptual processes were needed to explain both group and element movement in the Ternus display, Bruno Breitmeyer and his colleagues at the University of Houston (Breitmeyer et al 1988; Breitmeyer and Ritter 1986a, 1986b; Ritter and Breitmeyer 1989) developed the hypothesis that

> "... temporal integration of the pattern response to the two overlapping elements contributes to signaling this stationarity [during element movement]. Specifically, we further suggest that response persistence, since it in turn contributes to temporal integration of pattern ... plays a significant role in determining which of the two bistable percepts dominates." (Breitmeyer and Ritter 1986a, page 1802)

The research strategy was essentially to manipulate the Ternus stimuli in ways that had already been shown to affect the phenomenon of pattern persistence. Manipulations that were known to enhance pattern persistence were expected to increase reports of element movement. Thus, effects of ISI, frame duration, element size, contrast, and other viewing conditions (eg dichoptic and binocular viewing) were all interpreted in terms of pattern persistence, generally in support of the hypothesis. This hypothesis subsequently received independent support from the work of Casco (1990).

Even though many variables known to influence visible persistence (eg luminance, contrast, figure size, spatial frequency, and stimulus duration) produced results predicted under the visible-persistence hypothesis when applied to the Ternus display,

(1) The reference to 'lines' arises because Braddick and Adlard used lines instead of dots or circles in their displays.

Kramer and Rudd (1999) conducted several important tests of the hypothesis and rejected it. The strategy employed by Kramer and Rudd was to manipulate various form correspondence cues while simultaneously weakening, or even eliminating, the occurrence of visible persistence. In short, the researchers produced strong element movement under conditions that minimized or eliminated visible persistence, and they produced strong group movement under conditions that enhanced visible persistence. Ultimately, they drew the conclusions that visible persistence is neither necessary nor sufficient to explain element movement and that form correspondence plays a strong role in determining which percept dominates (contrary to the interpretation of Kolers 1972).

Since Kramer and Rudd's (1999) work, the visible-persistence explanation of the Ternus effect has been severely weakened.

2.3 *Two newer motion processes*

Approaches to understanding the qualitatively different percepts of the Ternus display that relied too heavily on specific physiological mechanisms or theoretical criteria eventually fell out of favor. In addition, the two-process theory may not have been generalizable enough to other motion displays to be useful. As we show here, one alternative approach was to classify the ways in which motion stimuli tend to differ and then to seek commonalities in the way(s) the visual system responds to them.

In a widely cited critique, Cavanagh and Mather (1989) contested the existence of separate long-range and short-range motion processes as had been previously used to explain group and element motion in the Ternus display. Their argument was based on exceptions, or at least counter-arguments, to what they considered to be the defining criteria for short-range and long-range processes. For example, whereas Braddick (1980) had argued that the short-range motion process could not respond to equiluminant color stimuli, Cavanagh and Mather (1989) cited research that showed how equiluminant stimuli could indeed lead to motion percepts under conditions that otherwise favored the hypothetical short-range process.

In place of the short-range/long-range distinction, Cavanagh and Mather (1989) recommended a distinction between 'first-order' and 'second-order' stimuli based on their statistics.

> "First-order statistics specify the frequency with which individual points in an image have specified intensity or colour values. ... Second-order statistics define the frequency with which specific combinations of intensity or colour values occur for *pairs* of points ... ." (page 106)

Having defined the stimuli, it became possible to distinguish new categories of motion processes, ie first-order and second-order motion processes. Thus,

> "a first-order motion process responds to the displacement of first-order differences in luminance and perhaps colour" [and] "a second-order motion process, if such a process exists, would respond to displacement of second-order differences in luminance or colour, even in the absence of first-order differences." (page 106)

In the view of Cavanagh and Mather, the same underlying principles of motion detection and analysis served both first-order and second-order phenomena; only some of the details of processing differed. Because their purpose was more general, Cavanagh and Mather unfortunately failed to describe how such a distinction would explain the bistability of the Ternus display and the differences in stimulus conditions that tended to produce different percepts from the same alternating stimuli.

In part because Cavanagh and Mather (1989) failed to account for the existence of two different percepts in the same visual display, Petersik (1991) replied to Cavanagh and Mather, arguing that when one examines the data obtained from a single paradigm (ie the Ternus display) the short-range/long-range distinction has more explanatory power than the first-order/second-order distinction. Cavanagh (1991) responded to Petersik's critique by addressing the percepts associated with the Ternus display. He pointed to the existence of a 'cyclopean Ternus display' (Patterson et al 1991) as evidence that the short-range/long-range distinction was not valid. Patterson et al used stereoscopic random-dot displays to recreate a Ternus display in which the elements were not defined by luminance. It was found that both group and element movement could be obtained with such a display. According to Cavanagh, since element movement had been associated with the short-range process, and since the short-range process had been effectively 'unplugged' by Patterson et al's stimuli, but element movement was nonetheless perceived, the short-range/long-range distinction could not be valid.

However, Petersik (1994) pointed out that the existence of an element-movement-like percept with dynamic cyclopean stimuli did not logically prevent the element movement obtained with luminance-domain stimuli from being attributable to the short-range process. Instead, the percepts obtained with the cyclopean stimuli required a refinement in our understanding of the flexibility of the long-range system. Ultimately, Petersik recommended the retention of the short-range/long-range distinction, but encouraged its theoretical development.

In empirical research, Petersik (1995) generated several second-order versions of the Ternus display; that is, displays in which the elements engaged in Ternus motion were not defined by luminance contrast. In one case, figures were defined by binocular disparity; in another, by phase shifts in periodic luminance patterns; in yet another, by relative motions of pixels; and in a last case, by orientation of small line segments. A number of additional variations between the Ternus elements and their backgrounds were introduced, along with the manipulation of the traditional ISI. Like Petersik et al (1978) and Patterson et al (1991), Petersik (1995) was able to obtain both element and group movement with the second-order stimuli, and the movement seen was—in part—dependent upon ISI. However, across stimulus types, Petersik found some very different patterns of response as functions of the manipulations made. On the basis of these results, he argued against the possibility of a single family of homogeneous second-order motion detectors as was suggested by the position taken by Cavanagh and Mather (1989).

Given the weaknesses in both the two-motion-process account and the first-order/second-order distinction, it is likely that neither one alone accounts for all the phenomena obtained with the Ternus display. In view of this, it is indeed relevant to ask whether two processes are even needed to explain the Ternus percepts, or whether a single motion-analyzing process with two different outputs would suffice. First, the apparent lower-level vs higher-level difference between element movement and group movement [as revealed, for example, by difference produced by dichoptic viewing, eg Pantle and Picciano (1976)] seems to impose a related structural separation of processes. Second, on a logical level when dealing with something as complicated as brain systems, it may not be useful to try to discriminate between two processes, each with its own output, and a single process with two alternative outputs—functionally they are much the same and leave many of the same questions to be answered.

2.4 *Group and element movement as the products of neural-network processing*

By the early 1990s the main explanatory issue regarding the Ternus phenomenon was primarily over the nature of the process or processes that were allegedly involved. With no clear answer emerging, some researchers turned to the process-free, mechanism-free, pathway-free, approach of neural-network modeling. As this section demonstrates, the neural-network approach had the advantage of requiring theorists to be very specific about the computations performed and transformations made by the various units of a network. Also, the various 'constraints' that had entered the language of perception now had to be turned into precise computations. Another advantage of the network approach was that the models could be tested against empirical results quite nicely. Nonetheless, after a few initial positive attempts to model the percepts associated with the Ternus display, efforts ceased.

In the late 1980s computer simulation of psychological processes advanced with the publication of the two volumes of *Parallel Distributed Processing* (McClelland et al 1986; Rumelhart et al 1986). In short order, many researchers were constructing their own 'neural-network models' to simulate processes that had previously been more vague and hypothetical. One of the advantages of the network modeling approach was that it required theorists to be specific about how particular constructs were to be embodied and function. Additionally, attempts were often made to incorporate knowledge of brain systems in the models.

Since the Ternus display produced fairly reliable results and had a fairly sizable published literature regarding it, at least two laboratories independently attempted to design plausible large-scale systems consisting of neuron-like components that would predict the occurrence of group and element movement under the conditions known to facilitate and antagonize them. Grossberg's group (Grossberg 1991; Grossberg and Rudd 1989, 1992) modeled group and element movement in the context of the short-range/long-range distinction. The key to the model developed by this group was the 'MOC filter' (Motion, Oriented, Contrast-sensitive filter). The MOC filter consists of several levels of processing or filtering, each of which was designed on the basis of physiological and/or psychophysical data. Thus, for example, early levels of filtering include center/surround receptive-field antagonism, 'sustained' and 'transient' channel properties, etc The output of the overall MOC filter is a directionally selective response with characteristics that conform well to higher-level perceptual phenomena.

With respect to the Ternus display, either element or group movement can be produced by the model, depending upon ISI. Essentially, longer ISIs are required to activate transient 'cell' filtering, which includes a form response based on the output of a Gaussian filter of all three elements in a frame (in which the peak activity resides at the center of gravity of the group). As regards transient responses, the MOC filter constructs an output based on the motion of the group of three elements back and forth.

In the absence of transient-cell activation, there is a sustained output at the locations of the 'overlapping' elements in the Ternus display; hence, element movement is perceived. That is, the outer elements of the display are 'matched' over space and time. Grossberg's model has undergone considerable revision since Grossberg and Rudd applied it to the Ternus display (eg Grossberg et al 2001); however, we are not aware that newer versions have been tested with the Ternus display.

In contrast to Grossberg's motion-filter approach, Dawson (1991) designed a global, massively parallel network in which every processing unit is connected to every other processing unit. According to Dawson,

> "the model is an *autoassociative network* that iteratively modifies the activation pattern of a set of simple interconnected processing units (representing local measurements) until a stable pattern is achieved (representing a *global interpretation*)." (pages 573–574)

A key to Dawson's model was the incorporation of three 'constraints' that research has identified as important to apparent-motion perception: all else equal, motion tends to occur between nearest neighbors, abrupt discontinuities in velocities are avoided, and the splitting or fusing of elements is avoided. Dawson et al (1994) later added a fourth constraint, the polarity-matching constraint, which established a preference for correspondence matches between elements of the same contrast polarity (see section 2.5).

A further key to the model is that a major purpose was the maintenance of identities of elements in motion.

Since the assignment of element identity across frames was a central issue for Ternus, it was natural for Dawson to test his model using the Ternus display. It was found that either element or group movement could be obtained, depending upon the status of a single parameter in the model. Although two solutions being generated by a single model appears to support Cavanagh and Mather's (1989) contention that a single motion process underlies all motion percepts, Dawson wrote: "... the network's performance does not entail a rejection of the two-process distinction. This is because although the network maintains the identity of moving elements, it does not represent their movement" (page 582). Dawson argued that it is important to maintain a distinction between processes that assign identity and those that determine movement. Following his review of the literature and after examining the outputs of his model, Dawson suggested that the two processes in motion perception are (a) a low-level motion detector and (b) an attentional tracking system (cf Cavanagh 1992).

2.5 *A return to principles of perceptual grouping*

Here we demonstrate that the most recent explanations of the Ternus effect have returned to a form that Ternus would probably recognize: Gestalt grouping. As Kramer and Yantis (1997) suggest, what remains is to determine the operating principles of and weights applied to the spatial grouping effects and temporal grouping effects under different conditions. Also, there is a need to recognize the role that various background contexts can play in influencing the grouping effects.

Ternus himself attempted to influence the perception of group and element movement largely by manipulating the spatial positions of stimulus elements between frames. However, a number of more recent efforts have been made to investigate the effects of the spatial form, or details, of the Ternus elements. For example, following the lead of Pantle and Picciano (1976), Dawson et al (1994, Experiment II) used both black and white Ternus elements, either maintaining contrast polarity at the same spatial locations across frames or maintaining contrast polarity within groups across frames. When the contrast polarity was consistent for the 'overlapping' elements, element movement was favored. When polarity was consistent within the group of three elements across frames, group movement persisted. Dawson et al (1994) used these results, along with others, to argue in favor of adding a 'polarity-matching constraint' to the apparent-movement network model of Dawson (1991) described in the previous section.

Similarly, Scott-Samuel and Hess (2001) manipulated the spatial structure of the Ternus elements across frames. In one experiment, the elements consisted of noise pixels that were sinusoidally modulated to produce vertical grating bars. The spatial phase of the gratings in stimulus frame 1 vs stimulus frame 2 was subsequently manipulated. In short, when the spatial phase of the elements was consistent across frames, element movement was favored; when it differed by roughly $90° - 270°$, group movement was more favored (especially at 180°). On various grounds, Scott-Samuel and Hess interpreted their results as evidence against a role for the short-range process in the Ternus display. Instead, they argued that both element and group movement are produced by a long-range, feature-based process in apparent movement.

In one of their experiments, Alais and Lorenceau (2002) made the Ternus elements from oriented Gabor patches. In one condition of the experiment, all Ternus elements were vertically oriented (parallel); in another, horizontally oriented (collinear). Compared to a control condition, the parallel Ternus elements produced a slight bias toward group movement, whereas the collinear elements produced a slight bias toward element movement. Alais and Lorenceau interpreted their results as evidence for the existence of 'association fields' in apparent movement. Association fields are hypothetical constructs that provide some perceptual processing advantage to collinear elements within the field's perimeter.

Rather than manipulate the spatial structure of the Ternus elements themselves, Petersik and Rosner (1990) constructed displays consisting of two vertically separated rows of Ternus elements. On any frame of the displays, particular elements in each row were connected by gray lines. The positioning of the lines was varied across frames, along with the typical element shifts used in the Ternus displays. Petersik and Rosner found that when the connecting lines between the "overlapping" elements remained stationary, a bias to report element movement (in the target row) resulted. Similarly, when the terminals of the connecting lines in the target row shifted between frames, a bias to report group movement resulted. The authors offered two possible explanations for their results, one based on the short-range/long-range distinction and the other based on cognitive influences. However, the authors did not consider that their effects may have been based on Gestalt-like context effects on grouping preferences.

In addition to examining the influence of the spatial structure of Ternus elements in their experiment 1, Kramer and Yantis (1997) ran an extensive set of experiments designed to assess the effects of context on element vs group movement. In the first case, when the shape of an 'overlapping' element remained constant across frames, element movement was preferred. Much like Petersik and Rosner (1990), Kramer and Yantis also found context influences on the Ternus display: In the case of the context experiments, background contexts that encouraged the stationary appearance of the middle elements of the Ternus display tended to favor element movement. Contexts that encouraged the perception of a displaced group of elements across frames indeed favored group movement.

To account for their results, Kramer and Yantis (1997) introduced two different kinds of grouping effects:

> "Effects caused by the configuration of elements within a single array will be referred to as *spatial grouping effects* (which includes effects referred to in the literature as 'context effects'). Across successive frames of elements, temporal grouping by proximity (in time) and similarity will also depend upon the appearance and locations of the elements and, in addition, on the timing of the successive frames. The influence of proximity and similarity across time will be referred to as *temporal grouping effects* (because they depend in particular on the matching of individual elements across time)." (pages 87–88)

According to Kramer and Yantis, in the Ternus display there is a competition between spatial and temporal grouping effects, and anything that favors one type of grouping will also favor element or group movement (the former associated with temporal grouping and the latter with spatial).

He and Ooi (1999) examined similar grouping effects and concluded that "when the grouping tendency among tokens [ie Ternus elements] in the same frame is strong, a group motion will be perceived ... [and] when the grouping tendency between inner tokens across frames is strong, an element motion will be perceived" (page 891). As their discussion shows, He and Ooi were very aware of the similarity of the grouping effects they (and Kramer and Yantis 1997) discussed and the identity effects originally described by Ternus.

Despite the success of the above demonstrations, however, it is apparent that not all grouping effects can bias reports of 'group' and 'element' movement in the Ternus display. Dodd et al (2005) used neo-Gestalt grouping principles previously investigated by Palmer and Rock (1994) in an attempt to create perceptual 'single units' of the Ternus stimuli and thereby eliminate element movement. Nonetheless, element movement was perceived with such stimuli; indeed there was not even a significant bias in the production of group movement. The authors used their data to argue against the two-process distinction, but it is difficult to see how results that are exactly in accord with the predictions of the two-process notion can be used against it.

2.6 *A new application of the phenomenon*
Since the 1970s at least there has been some effort to relate the two possible percepts obtained with the Ternus display to different neural systems. This way of explaining the Ternus display has culminated in the attempt to relate group movement to magnocellular function and element movement to parvocellular function.

Renewed interest in the physiological basis of the percepts associated with the Ternus effect may have been stimulated by the observation made by Slaghuis et al (1996) that dyslexics tend to see less element movement across ISIs than do non-dyslexics. This finding was later replicated and refined by Cestnick and Coltheart (1999), who also were the first to explicitly identify group and element movement with magnocellular and parvocellular processing per se. Still others have reported similar findings (see Skottun 2001 for a review).

The more recent attempts to relate apparent-movement percepts to distinct physiological pathways seems somewhat less based on theoretical constructs than in the past. As Skottun (2001) has stated:

> "The theory was initially cast in terms of the psychophysically defined 'transient' and 'sustained' systems but was later recast in terms of the anatomically defined 'magnocellular' and 'parvocellular' systems. ... [Their similarities] should not be taken to mean that the magnocellular and parvocellular systems can be assumed to correspond to the transient and sustained systems in all regards. There may be subtle differences that may be significant with regard to other issues and in other contexts." (page 1449)

This caveat serves as a reminder of the difficulty one faces when attempting to infer physiological function from psychophysical results (cf Teller 1984).

The work of Slaghuis et al (1996) and Cestnick and Coltheart (1999) not only re-established a connection between the two percepts of the Ternus display with distinct physiological subsystems, but it laid the groundwork for using the Ternus display as a tool to study dyslexia and perhaps as a potential screening device. However, this approach has been criticized by Skottun (2001) and by Scott-Samuel and Hess (2001), and it is not clear how widely accepted these positions are today. A recent review of the literature (Ramus 2003) cited the magnocellular-deficit theory of dyslexia, but also pointed out that there are several empirical findings inconsistent with it.

3 Conclusions
As discussed in section 1, persistent explanations of perceptual phenomena tend to be those that are tied to objective mechanisms. In that context, the Ternus effect seems to be no exception, since from the mid-1970s to the present there has been interest in finding a separate physiological mechanism or 'pathway' mediating element movement and group movement each. For those who remain interested in determining the physiological basis of the Ternus phenomenon, a focused brain-imaging study on the two percepts is needed.

In this paper we have traced explanations of the Ternus effect from Ternus's original paper up to the present. We have shown that both Ternus himself and some contemporary theorists (eg He and Ooi 1999; Kramer and Yantis 1997) have emphasized the role of Gestalt grouping (and the influence of spatial and temporal factors upon such grouping) in the production of group and element movement. Working specifically with the framework presented by He and Ooi, in as-yet unpublished research we have also shown that within-frame biases of element features (formations of comparable Gestalt groups across frames) indeed favor the percept of group movement, whereas between-frame biases of element features (maintenance of features in the same locations across frames) favor element movement, regardless of ISI (see figure 2). We take this evidence that the organization of features 'belonging to' the larger figural elements selectively biases the percept obtained in the Ternus display to be support for the positions of all of the above-named authors. In a way that might have been agreeable to Ternus's way of thinking, such findings can be interpreted to mean that local features add an extra layer of identity to an object. Thus, the arrangement of local features on otherwise ambiguous global 'objects' can determine which objects have remained in a single position and which have moved. In short, local features can determine whether Gestalt groupings are maintained or change over time.

We close with the argument that after having reviewed the literature, we find none of the leading explanations completely satisfying. Although 'identity' based upon perceptual group membership vs absolute spatial location offers insight to perceptual codes and is a useful heuristic, explanations that rely on identity also have a component of tautology built in. That is, reference to identity within a group almost necessarily implies a group movement, while reference to identity in terms of location almost necessarily implies stationary central elements in element movement. How, when, and why the visual system enacts such identities remains unanswered. It thus appears that a completely useful, unambiguous, realistic explanation of the Ternus effect has not yet been found.

Under any circumstances, a good explanation of the Ternus effect will have to provide answers to the following questions: (a) why element and group movement occur under the particular conditions that favor them (ie how do those conditions favor them); (b) why element and group movement look the way they do; (c) why the percepts associated with the Ternus display are mutually exclusive; and (d) why the two percepts alternate when the display is viewed for a prolonged period of time: if the display is viewed sufficiently long, perceptual alternation is obtainable over a very wide range of ISIs; however, it is most easily obtained with intermediate ISIs. Finally, any explanation of the Ternus effect needs to be compatible with a more general, acceptable, theory of motion perception. Thus, theories of motion perception need to explain not only the Ternus phenomenon, but all other acknowledged effects in motion perception. In our opinion, Grossberg and his colleagues (eg Grossberg 1991; Grossberg et al 2001; Grossberg and Rudd 1989, 1992) have made the most vigorous attempts to reach such a goal.

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References

Alais D, Lorenceau J, 2002 "Perceptual grouping in the Ternus display: Evidence for an 'association field' in apparent motion" *Vision Research* **42** 1005 – 1016

Asch S E, 1952 *Social Psychology* (New York: Prentice Hall)

Attneave F, 1971 "Multistability in perception" *Scientific American* **225**(6) 62 – 71

Boring E G, 1942 *Sensation and Perception in the History of Experimental Psychology* (New York: Appleton – Century)

Bozzi P, 1939/1969 *Unita, Identita, Causalita* (Bologna: Cappelli) [Originally published in 1939]

Braddick O J, 1973 "The masking of apparent motion in random-dot patterns" *Vision Research* **13** 355 – 369

Braddick O J, 1974 "A short-range process in apparent motion" *Vision Research* **14** 519 – 527

Braddick O J, 1980 "Low-level and high-level processes in apparent motion" *Philosophical Transactions of the Royal Society of London B* **290** 137 – 151

Braddick O J, Adlard A J, 1978 "Apparent motion and the motion detector", in *Visual Psychophysics and Physiology* Eds J Armington, J Krauskopf, B R Wooten (New York: Academic Press) pp 417 – 426

Breitmeyer B G, 1984 *Visual Masking: An Integrative Approach* (New York: Oxford University Press)

Breitmeyer B G, Ganz L, 1976 "Implications of sustained and transient channels for theories of visual pattern masking, saccadic suppression, and information processing" *Psychological Review* **83** 1 – 36
Breitmeyer B G, May J G, Williams M C, 1988 "Spatial frequency and contrast effects on percepts of bistable stroboscopic motion" *Perception & Psychophysics* **44** 525 – 531
Breitmeyer B G, Ritter A, 1986a "The role of visual pattern persistence in bistable stroboscopic motion" *Vision Research* **26** 1801 – 1806
Breitmeyer B G, Ritter A, 1986b "Visual persistence and the effect of eccentric viewing, element size, and frame duration on bistable stroboscopic motion percepts" *Perception & Psychophysics* **39** 275 – 280
Casco C, 1990 "The relationship between visual persistence and event perception in bistable motion display" *Perception* **19** 437 – 445
Cavanagh P, 1991 "Short-range vs. long-range motion: Not a valid distinction" *Spatial Vision* **5** 303 – 309
Cavanagh P, 1992 "Attention-based motion perception" *Science* **257** 1563 – 1565
Cavanagh P, Mather G, 1989 "Motion: The long and short of it" *Spatial Vision* **4** 103 – 129
Cestnick L, Coltheart M, 1999 "The relationship between language-processing and visual processing deficits in developmental dyslexia" *Cognition* **71** 231 – 255
Dawson M R W, 1991 "The how and why of what went where in apparent motion: Modeling solutions to the motion correspondence problem" *Psychological Review* **98** 569 – 603
Dawson M R W, Nevin-Meadows N, Wright R D, 1994 "Polarity matching in the Ternus configuration" *Vision Research* **34** 3347 – 3359
Dawson M R W, Wright R D, 1994 "Simultaneity in the Ternus configuration: Psychophysical data and a computer model" *Vision Research* **34** 397 – 407
Dodd M D, McAuley T, Pratt J, 2005 "An illusion of 3-D motion with the Ternus display" *Vision Research* **45** 969 – 973
Grossberg S, 1991 "Why do parallel cortical systems exist for the perception of static form and moving form?" *Perception & Psychophysics* **49** 117 – 141
Grossberg S, Mingolla E, Viswanathan L, 2001 "Neural dynamics of motion integration and segmentation within and across apertures" *Vision Research* **41** 2521 – 2553
Grossberg S, Rudd M E, 1989 "A neural architecture for visual motion perception: Group and element apparent motion" *Neural Networks* **2** 421 – 450
Grossberg S, Rudd M E, 1992 "Cortical dynamics of visual motion perception: Short-range and long-range apparent motion" *Psychological Review* **99** 78 – 121
Guillaume P, 1937 *La Psychologie de la Forme* (Paris: Flammarion)
He Z J, Ooi T L, 1999 "Perceptual organization of apparent motion in the Ternus display" *Perception* **28** 877 – 892
Kaufman L, 1974 *Sight and Mind* (New York: Oxford University Press)
Kolers P, 1972 *Aspects of Motion Perception* (New York: Pergamon Press)
Kramer P, Rudd M, 1999 "Visible persistence and form correspondence in Ternus apparent motion" *Perception & Psychophysics* **61** 952 – 962
Kramer P, Yantis S, 1997 "Perceptual grouping in space and time: Evidence from the Ternus display" *Perception & Psychophysics* **59** 87 – 99
McClelland J L, Rumelhart D E, and the PDP Research Group, 1986 *Parallel Distributed Processing: Explorations in the Microstructure of Cognition* volume 2: *Psychological and Biological Models* (Cambridge, MA: MIT Press)
Metzger W, 1936 "Von gesehener Bewegung", in *Gesetze des Sehens* (Frankfurt am Main: Kramer) [Translated as chapter 16: *Perceived Movement* (Translator U Neisser) http://people.brandeis.edu/~sekuler/metzgerChapter/]
Palmer S, Rock I, 1994 "Rethinking perceptual organization: the role of uniform connectedness" *Psychonomic Bulletin and Review* **1** 29 – 55
Pantle A J, Petersik J T, 1980 "Effects of spatial parameters on the perceptual organization of a bistable motion display" *Perception & Psychophysics* **27** 307 – 312
Pantle A J, Picciano L, 1976 "A multistable movement display: Evidence for two separate motion systems in human vision" *Science* **193** 500 – 502
Patterson R, Hart P, Nowak D, 1991 "The cyclopean Ternus display and the perception of element versus group movement" *Vision Research* **31** 2085 – 2092
Petersik J T, 1989 "The two-process distinction in apparent motion" *Psychological Bulletin* **106** 107 – 127
Petersik J T, 1991 "Comments on Cavanagh and Mather (1989): Coming up short (and long)" *Spatial Vision* **4** 291 – 301

Petersik J T, 1994 "Conceptualizations of short-range and long-range processes in apparent movement" *Theory & Psychology* **4** 405 – 431
Petersik J T, 1995 "A comparison of varieties of 'second-order' motion" *Vision Research* **35** 507 – 517
Petersik J T, Hicks K I, Pantle A J, 1978 "Apparent movement of successively generated subjective figures" *Perception* **7** 371 – 383
Petersik J T, Pantle A J, 1979 "Factors controlling the competing sensations produced by a bistable stroboscopic motion display" *Vision Research* **19** 143 – 154
Petersik J T, Rosner A, 1990 "The effects of position cues on the appearance of stimulus elements in a bistable apparent movement display" *Perception & Psychophysics* **48** 280 – 284
Pikler J, 1917 *Sinnesphysiologische Untersuchungen* (Leipzig: Barth)
Pléh C, 1997 "Hungarian contributions to modern psychology", retrieved 28 May 2004 from http://www.staff.u-szeged.hu/~pleh/english/articles/hungpsy.html
Ramus F, 2003 "Developmental dyslexia: Specific phonological deficit or general sensorimotor dysfunction?" *Current Opinion in Neurobiology* **13** 212 – 218
Ritter A D, Breitmeyer B G, 1989 "The effects of dichoptic and binocular viewing on bistable motion percepts" *Vision Research* **29** 1215 – 1219
Rumelhart D E, McClelland J L, and the PDP Research Group, 1986 *Parallel Distributed Processing: Explorations in the Microstructure of Cognition* volume 1: *Foundations* (Cambridge, MA: MIT Press)
Scott-Samuel N E, Hess R F, 2001 "What does the Ternus display tell us about motion processing in human vision?" *Perception* **30** 1179 – 1188
Skottun B C, 2001 "On the use of the Ternus test to assess magnocellular function" *Perception* **30** 1449 – 1457
Slaghuis W L, Twell A J, Kingston K R, 1996 "Visual and language processing disorders are concurrent in dyslexia and continue into adulthood" *Cortex* **32** 413 – 438
Teller D Y, 1984 "Linking propositions" *Vision Research* **24** 1233 – 1246
Ternus J, 1926/1938 "Experimentelle Untersuchung über phänomenale Identität" *Psychologische Forschung* **7** 81 – 135 [English translation as "The problem of phenomenal identity', in *A Source Book of Gestalt Psychology* Ed. W D Ellis (1938, London: Routledge and Kegan Paul) pp 149 – 160]
Tolhurst D J, 1975 "Sustained and transient channels in human vision" *Vision Research* **15** 1151 – 1155
Ullman S, 1979 *The Interpretation of Visual Motion* (Cambridge, MA: The MIT Press)
Wallach H, 1935/1996 "Über visuell wahrgenommene Bewegungsrichtung" *Psychologische Forschung* **20** 325 – 380 [Translation into English with commentary by S Wuerger, R Shapley, N Rubin "On the visually perceived direction of motion", 1996 *Perception* **25** 1317 – 1367]
Wertheimer M, 1912 "Experimentelle Studien über das Sehen von Bewegung" *Zeitschrift für Psychologie* **61** 161 – 265

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