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Differential-activation theory can account for the Ternus display: Rejoinder to Petersik

Darko Odic
Department of Psychological and Brain Sciences, Johns Hopkins University,
3400 North Charles Street, Baltimore, MD 21218, USA; e-mail: darko.odic@jhu.edu

Jay Pratt
Department of Psychology, University of Toronto, Toronto, ON M5S 3G3, Canada

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Abstract. The Ternus display is a bistable apparent-motion display that has captivated researchers for decades. Recently, Odic and Pratt (2008, *Perception* **37** 1790 – 1804) provided evidence against the well-known two-process theory of Braddick and Adlard [1978, *Visual Psychophysics and Physiology* (New York: Academic Press) pp 417 – 426] and provided an explanatory framework using the differential-activation theory of Gilroy et al (2001, *Perception & Psychophysics* **63** 847 – 861). A comment by Petersik (this issue) challenges the methodology and theoretical implications of Odic and Pratt, and claims that the two-process distinction still has a role to play in the Ternus display. In this rejoinder, we examine the main points made by Petersik and expand on the differential-activation theory and its applicability to the Ternus display.

1 Introduction

The Ternus display is an apparent-motion paradigm with a long history in vision research. The display consists of three frames: in the first, three identical elements are presented in a line; then, an interstimulus interval (ISI), typically a blank screen, is presented for a nominal time; finally, the three elements are again displayed, but with all three displaced towards the right (see figure 1a). Depending on the duration of the ISI, two apparent-motion illusions are perceived: with short ISIs (< 50 ms), the leftmost element is seen to jump over the two middle elements ('element motion'), while with longer ISIs (> 50 ms), all three elements are seen to move together to the right ('group motion'—Pantle and Picciano 1976).

Recently, we (Odic and Pratt 2008) demonstrated that alternative motion perceptions of the Ternus display are possible. By selectively covering one of the three elements during the ISI with an equiluminant occluder, we found that, with the exception of the leftmost element, the occluded element was always seen as stationary, and the remaining moving objects were seen as moving to their nearest neighbour (see figure 1b). From this finding, we argued against the well-known two-process account of Braddick and Adlard (1978) and, instead, concluded that the data could be accounted for by the differential-activation theory (DAT) of Gilroy et al (2001).

Put succinctly, DAT suggests that apparent motion is detected by motion detectors that are sensitive to changes in luminance between the object and its background. Specifically, an object is perceived to move when the luminance of its spatial location changes towards the luminance of the background (ie becomes more similar to the background), while the luminance of a different spatial location increases away from the luminance of the background (ie becomes less similar to the background—see below for further discussion). We then expanded DAT to provide a general account of the Ternus display, suggesting several implications and extensions on the basic findings.

A recent comment by Petersik (this issue) has called the interpretation of our data into question. Specifically, Petersik objects to our argument against the two-process distinction, claiming that our findings are either interpretable by a two-process distinction

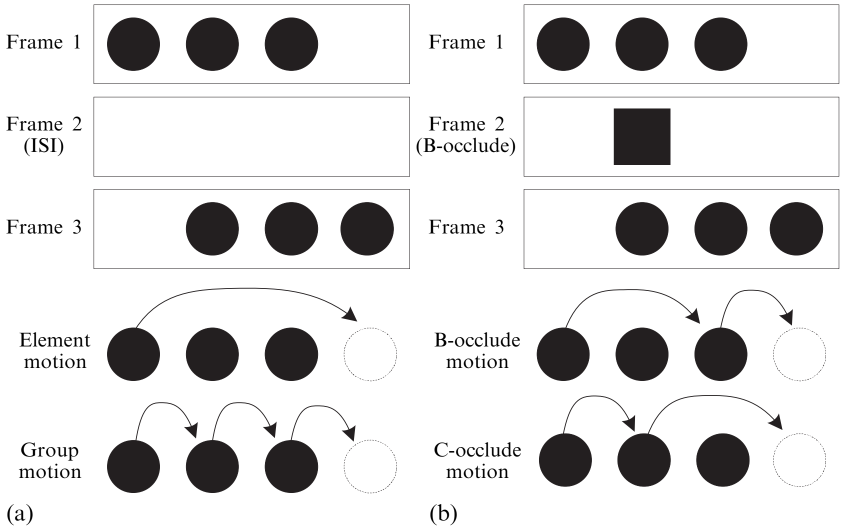

Figure 1. (a) A traditional Ternus display, and the control condition of Odic and Pratt (2008). Low ISIs result in the perception of element motion, high ISIs result in the perception of group motion. (b) One of the displays used in Odic and Pratt (2008), experiment 2. In the depicted scenario, the second element is occluded, and produces 'B-occlude motion'. When the first element is occluded, normal Ternus motions are perceived, and when the third object is occluded, 'C-occlude motion' is perceived.

or are so far removed from the typical Ternus display that no theory could account for them. Here, we examine the questions and comments raised by Petersik and address his concerns over our methods and interpretation. In the process, we also extend our theoretical account by demonstrating two unique ways in which DAT is compatible with solving the correspondence problem in the Ternus display, and how both versions point to the shortfalls of the two-process distinction.

1.1 *Methodological concerns*

We turn first to Petersik's comments on the logic of our paper and the methodology used. In response to our claim that our methods explicitly test Braddick and Adlard's (1978) account of the Ternus display, Petersik states that "the two-process distinction has never been rigorously formulated as a testable theory" (page 705) and that, therefore, "the 'theory' that Odic and Pratt refuted is a straw man" (page 707). It appears to us, however, that, whereas Petersik is referring to a more general two-process distinction (eg Petersik 1989), we are specifically referring to Braddick and Adlard's interpretation of this distinction in the context of the Ternus display.

Braddick and Adlard posit that there are two kinds of processes that underlie apparent-motion tracking: a short-range process (SRP) and a long-range process (LRP). Each process has its own set of parameters, with the SRP having very small spatial and temporal limits, and the LRP being a "more interpretive" and higher-level cognitive process, that selects corresponding elements based on Gestalt rules (Braddick and Adlard 1978, page 424). Within the context of the Ternus display, the Braddick and Adlard theory argued that the SRP is responsible for informing the LRP about the motion of individual elements. When the ISI is short, and the temporal limit of the SRP is not exhausted, the process can signal for the motion of the leftmost element and the non-motion of the central elements, and allows the LRP to interpret the configuration as element motion. However, "in the conditions of long or bright ISI, or dichoptic presentation, the low-level process is inactive and ... the higher-level process is free to behave like a good Gestaltist, and select its interpretation in light of the overall configuration, that is, the group motion that is generally perceived under these conditions" (page 425). Therefore, the account of Braddick and Adlard is specific, influential (eg Scott-Samuel and Hess 2001; Alais and Lorenceau 2002), and a testable theory.

We examined Braddick and Adlard's account of how group motion emerges, and found that group motion can be perceived with occluded elements, even at long ISIs when SRP should no longer be active. Therefore, we concluded that their theory is not a viable account for the Ternus display. Our proposed alternative, the DAT, is outlined in the following section.

In addition to the concern about the target of our paper, Petersik criticises certain aspects of our methods. He suggests that our Ternus display had "a complex spatio-temporal display that makes interpretation of the data vis-à-vis any theory difficult" (page 706). Petersik first argues that our Ternus display is atypical because each one of our trials is made up of a single sequence of Frame 1 – ISI – Frame 2. He suggests that this is unusual, as other researchers have not tested the Ternus display in this way, and participants often need more than one exposure before they see the motions clearly. However, other Ternus studies have used single sequences (eg Dodd et al 2005). Moreover, our control (ie non-occluder) conditions show that participants are fully capable of discriminating between element and group motions across ISIs. If anything, our findings point to the robustness and replicability of the Ternus display under varied conditions.

Petersik also notes that our ISI was atypical because of the presence of an occluder and argues that the SRP could have signalled non-motion with the occluder present. Several things suggest that this was not the case. First, the occluder was clearly not a circular element and, although it shared luminance with the Ternus elements, its onset was always sudden and noticeable. Furthermore, the first experiment had an occluder that spanned across the two elements and the gap in-between, and was, therefore, highly unlike the elements themselves. Second, there is no reason to assume that the SRP, as defined by Braddick and Adlard, could have tracked the elements across the occluder. As specified by Braddick and Adlard, the elements have a temporal limit of up to about 80 ms (Braddick 1974), and we detected element motion as long-lasting as 120 ms. Therefore, it is unclear why Petersik suggests that it is "easy to see" (page 707) that the SRP could have played a role.

1.2 *Theoretical concerns*

We now move on to some theoretical considerations brought up by Petersik. Earlier (Odic and Pratt 2008), we proposed that the DAT of Gilroy et al (2001; Gilroy and Hock 2004; Hock et al 2002, 2009) can account for our results. In this section, we will review and expand on our original proposal, and suggest that the DAT is incompatible with both the two-process distinction of Braddick and Adlard (1978) and the various two-process distinctions illustrated by Petersik (1989).

The DAT, as developed by Gilroy et al (2001), posits that apparent motion can be explained at the level of motion detectors. Specifically, Gilroy et al show that apparent motion is most readily perceived when the luminance of one spatial location changes towards the background luminance, while another location on the screen changes its luminance away from the background luminance (a 'cross-change'—Hock et al 2002). For example, given the presence of a single element on a black screen, the element is most often perceived to move when the luminance coming from the element's spatial location becomes that of the background (ie the element disappears), while a part of the background now changes towards the luminance of the element (ie the element reappears). Recently, Hock et al (2009) further developed their theory to show how the cross-change of luminance can predict apparent motion for both first-order and second-order changes (cf Cavanagh and Mather 1989), and therefore provides a unifying view at both apparent and real motion perception (Gilroy and Hock 2004; Hock et al 2009).

Owing to the complexity of DAT, we (Odic and Pratt 2008) chose to focus on only the most basic ideas within it—that the change in luminance is necessary for the activation of motion detectors and that the activation of motion detectors is sufficient for the perception of apparent motion. We proposed that each element in the Ternus display is tracked by a motion detector, and that the ISI creates the change in luminance necessary for the perception of motion. With longer ISIs, the change of luminance in the spatial location of each element is pronounced and, with long ISIs, all three objects are perceived to move. In conditions of short ISIs or when an equiluminant occluder prevents the change in luminance, only the leftmost element is seen to move, as its luminance changes towards the background in the third frame.

In order to account for the idea that luminance is examined across the three frames, we created the concept of a 'temporal summation of contrast' (TSC)—the idea that motion detectors sum changes in luminance over time at specific spatial locations and that a threshold value needs to be reached for each detector before it begins tracking motion. Thus, the relationship between ISIs and TSC is such that with higher ISI comes higher TSC, as the change in luminance is temporally longer and more pronounced, and higher TSC results in the activation of motion detectors, as the threshold of these detectors is reached. The TSC construct was created by us because the experiments performed by Gilroy et al (2001) did not explain the role of the temporal dimension on motion detectors. Nevertheless, we feel that the concept of the TSC is easily integrated within the DAT, and serves as a useful bridge between the apparent motions of Gilroy et al (2001) and the Ternus display.

Our account heavily stressed that luminance-sensitive motion detectors were responsible for informing the visual system which elements have moved. The account was, however, ambiguous in resolving where the correspondence problem is eventually solved. One proposed option was that the visual system solves the correspondence problem at a later stage of visual processing, probably by using a range of criteria and constraints as outlined by Dawson (1991), including the nearest-neighbour principle and an attentional tracking system. This option appears, at first, to be similar to suggestions of Braddick and Adlard (1978) and Petersik (1989). For example, Braddick and Adlard suggested that the SRP is, most likely, neural motion detection, and both Braddick and Adlard, and Petersik suggested that the LRP is an interpretive process that exists in higher-level vision.

We believe, however, that the similarities between the two-process theory and DAT are largely superficial. The distinguishing property of the two-process distinction is not that two unique processes are necessary for apparent motion, but that these processes are specifically the SRP and LRP (and their respective parameters). It is the nature of the two kinds of processes that the DAT strongly argues against. For example, Braddick and Adlard (1978) suggest that the neural detectors are inactive during the perception of group motion. Petersik (1989) cites several two-process theories that claim that the two processes compete over which Ternus illusion will be seen. The DAT, on the other hand, argues that the low-level detectors are *necessary* for any motion information to enter the visual system, and these detectors are always active and play a critical role in the perception of any motion, be it real or apparent, group or element (Gilroy and Hock 2004; Hock et al 2009). Although motion detectors must send motion signals that are integrated over time, it is not accurate to say that they have temporal or spatial limits that prevent them from functioning, and that alternative processes take their place. Group and element motion, therefore, cannot be seen as the product of one *or* the other, but a combined effort by both. In other words, despite positing a multi-process account of apparent motion perception, the DAT is not equivalent to the two-process distinction of Petersik (1989).

Furthermore, although not discussed in detail by us (Odic and Pratt 2008), the DAT could also account for the correspondence problem being solved within the motion detectors. This suggestion is more canonical to the work of Gilroy et al (2001), Hock et al (2002, 2009), and Gilroy and Hock (2004). Specifically, counter-change of luminance between two spatial locations activates *directionally specific* motion detectors, while simultaneously inhibiting detectors for other paths; motion detection is, therefore, the product of an ensemble of motion detectors that work cooperatively (Hock et al 1997a). The final product of the detectors is, therefore, not only a signal for which elements in the initial display have moved, but also where they have moved to. On this view, there is no need for a higher-level feature-tracking system (Hock et al 2009), or for a distinction between short-range and long-range processes.

These two versions of DAT can both account for a wide assortment of data, including our occluder conditions. We do not, at the present, have evidence which version provides the best account. The higher-level solution seems to be a more prevalent idea in the Ternus display literature but, once again, we stress that it should not be equated with the two-process distinction. The ensemble of motion detectors, however, is a very powerful and unifying theory, and may explain apparent motion more generally. Future research will help us decide which of the two versions is better. The importance for the present task, however, is that neither is compatible with the various two-process distinctions discussed by Petersik (1989).

1.3 *Issues within the differential-activation theory*

Petersik raises here two concerns with the DAT account of the Ternus display. First, he wants us to further specify exactly how TSC works, and provides several alternatives. These options raised by Petersik about TSC are all excellent, but they are all answerable only by targeted empirical studies. In line with the model outlined by Hock et al (2009), each motion detector may have subunits that monitor changes in the physical energy coming from each spatial location. If the amount of energy changes for a long enough period of time, the subunits result in the threshold level of the motion detector being reached, and subsequent activation. Because all biological systems must deal with noise in the environment, it is sensible that not every temporary change in luminance will produce an activation of the detector. Therefore, at low ISIs, even when flickers in the elements are perceptually detected, the activation of motion detectors is not necessary.

Petersik also puts forward evidence that shows that changes in contrast alone do not affect the Ternus display. For example, in Petersik and Pantle (1979) the ISI time was kept constant at a time associated with element motion, but the frame had various luminance values, ranging from those close to those of first and third frame to ones that were different. They found that background luminance did not alter the results up until the change amounted to about 0.3 mL, at which point the percept changed to that of group motion. This result does not invalidate DAT, but further supports the notion that the motion detectors tolerate some amount of noise. When the change in ISI luminance is low, and the ISI itself is short, the motion detectors do not notice a large enough difference in TSC, and they do not signal for the motion of the overlapping elements, resulting in element motion. When the change in ISI luminance is high, the change is noticed, even at short ISIs, and all elements are perceived to move.

Furthermore, Petersik and Pantle (1979) in their experiment 4 kept the background luminance constant, but varied the luminance of the elements so that they were either very unlike the background or similar to the background. They found that there was an effect of contrast, with the elements more similar to the background showing more group motion at intermediate ISIs. Despite Petersik's (this issue) assertion that this argues against the DAT, it is in line with two experiments done by Hock et al (1997a) and Gilroy and Hock (2004), in which they found that the closer the elements are to the luminance of the background, the more likely apparent motion of those elements will be perceived.

Petersik also cites the research of Kramer and Rudd (1999) and Casco (1990) as demonstrating that factors other than changes in contrast are driving apparent motion in Ternus displays. Neither of these studies held the identity of all Ternus elements constant, and both found that the form correspondence of elements slightly biased the perception of motion regardless of ISI.

There are two ways that DAT deals with the issue of form in the Ternus display. The first, compatible with the view that the correspondence problem is solved by a higher-end process, allows this process to work out the information passed from the motion detectors alongside criteria and constraints based on form and/or contrast polarity (Dawson et al 1994). We would expect this process to be most active in cases where the motion detectors are not the most reliable source of information (eg when the elements are identical). This suggestion is further backed by a recent study by Hollingworth and Francioneri (2009) who proposed that, in cases of ambiguous apparent motion, identity of objects plays a larger role than spatio-temporal correspondence.

Another possibility is that the same amount of luminance that moves away from the environment must also move towards it. Therefore, if motion detectors work through ensembles of motion paths, identity is matched when objects with similar luminance move from one spatial position to another (cf Gilroy and Hock 2004). In Kramer and Rudd, and Casco, for example, the larger elements have more luminance, and, once they disappear during the ISI, they can be matched up by motion detectors in the third frame.

In summary, we have proposed two different ways in which the correspondence problem is solved in the Ternus display when the elements have different identity. Neither of these solutions creates a problem for either version of the DAT, and both are fully testable empirically. We hope that future studies will shed more light on the complex issues surrounding identity and motion correspondence.

2 Conclusions

The Ternus display continues to be an enticing apparent-motion display. However, unless theories of the Ternus display make contact with the perception of apparent motion in general, they are telling us very little how the visual system perceives the world. To that extent, we hope that future research will abandon the two-process distinction, and focus, instead, on models closer to the differential-activation theory of Hock et al (2009) and computational model of Dawson (1991).

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