Clarifying the Triangular Circuit Theory of Attention and its Relations to Awareness
Replies to Seven Commentaries

David LaBerge
Department of Cognitive Sciences
University of California, Irvine
Irvine, CA 92717
U.S.A.

dlaberge@simons-rock.edu

ABSTRACT: Replies are given to the commentaries of the seven cognitive science experts. Additional circuit diagrams clarify thalamic operations in attention and basal ganglia operations by which motivation affects attention. Selection-by-suppression and negative priming are accounted for within frontal control areas. Confusions between the terms awareness and consciousness persist, owing to the powerful habit of using awareness as a synonym for consciousness. Leaving consciousness as an umbrella term to denote many loosely-defined aspects of experience, the term awareness denotes the aspect of experience in which attention is directed to bodily sensations, thereby involving the self in ongoing experience.

The responses to the commentaries are organized under three main headings: (1) anatomical properties of the triangular circuit of attention; (2) functions of the triangular circuit in attention; and (3) relations of attention to awareness and self-awareness.

1. Anatomical Properties of the Triangular Circuit of Attention

1.1. Newman's Emphasis of the Role of the Reticular Nucleus (RN) of the Thalamus in Selective Attention

Newman's thoughtful and interesting set of comments begins by highlighting the issue of the "missing link" in the triangular circuit as it is represented schematically in the three figures of the target (Psyche, 1998) article and in the reference (Consciousness and Cognition, 1997) article. The part of the circuit which is omitted in these figures is the group of neurons within the reticular nucleus (RN), which are clearly shown in the figures of the thalamo-cortical circuit in previous publications (LaBerge, 1995; LaBerge, Carter, & Brown, 1992). In order to emphasize the triangular form of the circuit relating three widely spaced areas of the brain, I did not draw in the details of the local circuitry of the thalamo-cortical circuit, which is nested within the triangular circuit. Therefore, I omitted not only the reticular nucleus neurons, but also the axon connections from cortical neurons to the thalamic neurons. The details of the segment of the triangular circuit lying between the thalamus and the site of attentional expression are shown in Figure 1 of the present set of replies. These connections complete the thalamo-cortical loop, which is assumed to be a major component of the thalamo-cortical circuit because it produces the *augmenting* of the cortical attended site activity. The reticular nucleus component of the thalamo-cortical circuit is the other major component of the thalamo-cortical circuit because it produces the *suppression* of the surrounding sites' activities. Together, these two components of the thalamo-cortical circuit produce, in simulations of the circuit operations (LaBerge, Carter, & Brown, 1992) an expression of attention by both enhancement of activity at the target site and suppression of activity at the surrounding sites. Therefore, when observing schematic figures of the triangular circuit in any of my publications, it is to be understood that the reticular nucleus neurons and corticothalamic axons are included in the triangular circuit.
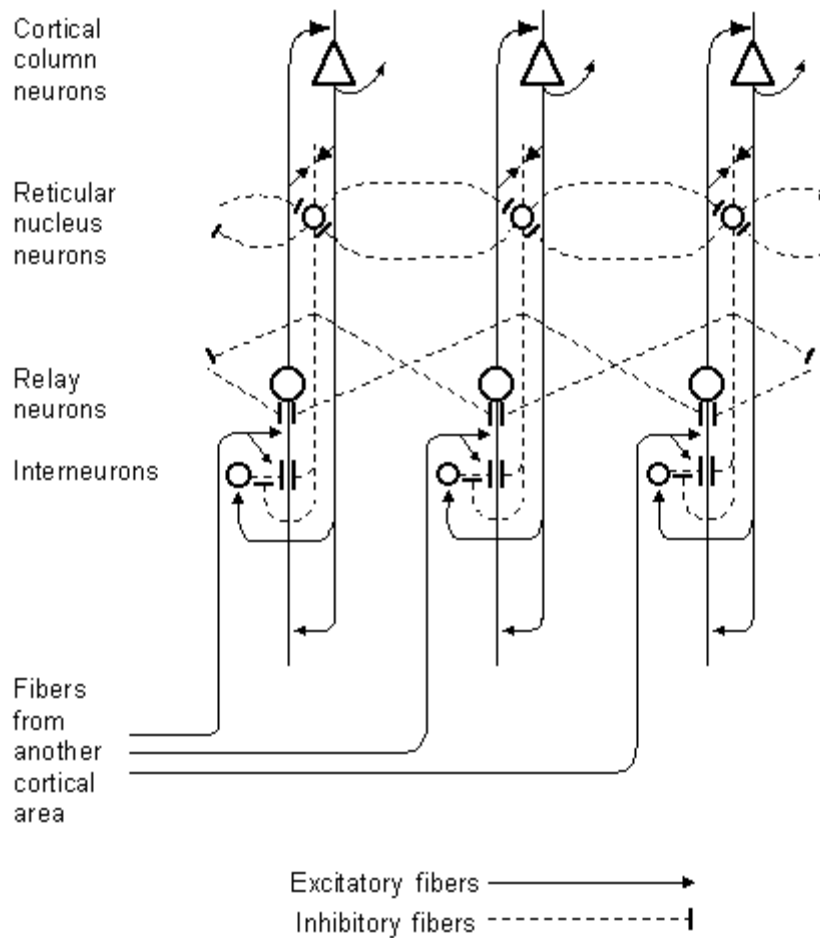
Figure   **1**
Three columns of the standard thalamocortical circuit. If expanded to an array of many columns, the center columns carry signals of a target and the outside columns carry signals of distractors. Afferent input to thalamic relay neurons from another cortical area is the indirect route of a triangular circuit; afferent input to the cortical column neurons (not shown) is the direct route of a triangular circuit (LaBerge, 1995). When a stimulus display contains a target with a distractor on each side (e.g., the display COG, with O as the target, and C and G as the distractors), top-down control activates center columns (at the thalamus) slightly more than the outside columns (for the display XOX, bottom-up sources do more of this); the circuitry then operates to produce (at the cortex) much more activity at the center columns than at the distractor columns (the simulation of this selection process is shown in LaBerge, Carter, & Brown, 1992).

Newman appears to assume that *the* reticular nucleus is the mechanism which produces the selective property of attention, following the models of Skinner and Yingling (1977) and Newman and Baars (1993). On this view, selective attention would seem to be produced by the suppression of activity in sites surrounding the attended site, without the addition of activity to the attended site. To my mind, there appears to be an anatomical problem with models that use the RN alone as the mechanism of selection. The problem concerns the control of what site in the RN shall be selected (presumably by activating RN neurons serving the surrounding non-attended sites, leaving the attended site

uninhibited and therefore expressing higher activity relative to the surrounding sites). If the selection of a particular object location in a cluttered field requires that frontal neurons directly activate RN neurons (as in the Skinner & Yingling (1977) model), then direct connections must exist between frontal areas and the RN, particularly the portion of the RN which serves the thalamo-cortical loop of the posterior cortex, where attention to object locations and object attributes are coded. However, to my knowledge, the anatomical tracing evidence does not show direct connections between the frontal cortex and the posterior portion of the RN (it does show direct connections between the frontal cortex and the anterior portion of the RN in the standard thalamocortical circuit, see Figure 1). Indirect connections between frontal cortex and posterior portions of the RN exist; in particular the frontal cortex sends fibers to the pulvinar, which in turn activates RN neurons as well as cortical sites where attention to objects is expressed. But this route of indirect connection between frontal control areas and the posterior cortical area in which selective attention is expressed is the route of attentional control assumed by the present triangular circuit theory, in which selection takes place not only by distractor suppression but also by target enhancement.

The known connections between frontal cortex and the basal ganglia do not provide an alternative indirect route to the posterior RN, because the output fibers from the basal ganglia do not project to the posterior RN. A third indirect alternative to consider is the anterior RN, to which the frontal areas are known to send fibers. Could the neurons of the anterior RN influence the neurons of the posterior RN in a manner that would produce the desired selective attention effect? The problem with this alternative is that RN neurons are exclusively inhibitory, and when one neuron is activated, it inhibits the neurons to which it is connected (via both axon-to-dendrite and dendrite-to-dendrite connections). Therefore, when one region of the RN is activated, the activity tends to be confined to only that region, and there is no spread of influence across regions of the RN. This inference is based on the assumption that the brain is in the waking state. When the brain is in the state of resting sleep, the RN neurons are hyperpolarized to a level which produces rebound bursts of spikes (Steriade, Jones, & Llinas, 1990), which in turn hyperpolarizes neighboring RN neurons so that they produce similar high rates of discharge. The result is that the rhythmic inhibitory firing of the RN cells spreads throughout the entire reticular nucleus, so that EEGs across all areas of the cortex become synchronized. Thus, owing to the different neuromodulatory regulation of RN neurons (from the brainstem) during sleep and waking, activity induced in one part of the RN influences other parts of the RN during resting sleep but not during waking.

1.2. The Thalamus and Feature-Binding

Newman reminds us of the hypothesis that the thalamocortical circuit may generate a 40-Hz (gamma band) oscillation by which activities in diverse cortical areas could be bound together, thereby forming a basis for the unitary perception of the several features of an object. The assumptions of the present version of the triangular circuit theory neither

affirm nor deny feature binding by synchronous oscillations of activity in diversely located cortical sites.

1.3. The Ventrolateral Nucleus of the Thalamus

Finally, in the section on Top-Down Control, Newman discusses the connections between the frontal cortex, basal ganglia, and thalamus, which are major players in the control of attention, according to the triangular circuit theory. There appears to be a misunderstanding of a particular anatomical connection when I describe the "ventrolateral nucleus, which connects with both the frontal areas and the basal ganglia" (on p.163 in the reference article). He states that "this is not entirely accurate. The ventrolateral nucleus does receive inputs from PFC via the basal ganglia, but projects to the motor/premotor cortex behind PFC". By my reading of the evidence, his statement about the connections between the ventrolateral nucleus, the PFC, and the motor/premotor areas is correct. But I believe that my statement about the ventrolateral nucleus and the frontal cortex is also correct, since the frontal lobe includes the cortical areas anterior to the central gyrus, which includes the motor and premotor areas. The interrelationship of the ventrolateral nucleus, the basal ganglia, and frontal areas is outlined in more detail in an upcoming publication (LaBerge, Auclair, & Sieroff, 2000). This paper describes changes in the intensity of preparatory attention in terms of changes in modulation of attention in premotor cortex, which in turn is influenced by changes of motivational interest in parts of the visual field, represented by changes in basal ganglia output to the ventrolateral nucleus.

1.4. Frontal Lobes and the Definition of Attention

In the second section of his commentary, Cave asks for a clarification of how attention is defined, and whether the frontal-controlled triangular circuit constitutes the "whole story of attention". He then states that "much of the work of attentional selection can be performed by lower-level mechanisms". I believe that there is a possible confusion between the concepts of selection and attention, which may arise from the particular way I am proposing to define attention. In the target article (1998), the third sentence of the Introduction reads: "Attention is assumed here to be an event in the brain consisting of simultaneous neuroactivity in three areas, which are interconnected by a triangular circuit;" and in the reference article (1997), the first sentence of the Abstract states: "It is proposed that attention to an object requires the simultaneous activity of three brain regions that are interconnected by a triangular circuit. The regions are the cortical site of attentional expression, the thalamic enhancement structure, and the prefrontal area of control." The definition of attention given in these sources does not state that attention is necessary for selection to occur. Selection of an object, it is commonly believed, often occurs prior to attention, for example, when an object abruptly appears in a display (e.g., Yantis, 1993), or when a display contains a feature singleton (e.g., Treisman & Gelade,

1980). Given the high frequency in which these pre-attentive selective operations occur in our everyday lives, I agree with Cave that much of the burden of selection is carried by the lower-level processes which serve pre-attentive selection. Therefore, a great deal of everyday selection appears to be "automatic".

In the interest of clarifying the present view of attention, I will try to place it within a larger context rather than characterizing attention as simply noting or registering the occurrence of a particular object. According to the present definition of attention, attention is concerned with what happens after the initial preattentive selection process occurs. The person who suddenly raises their hand or the person wearing the only red coat in the room will evoke our attention only if our higher-level processes return activation to the sites where the hand and red coat are coded. When the raised hand and red coat are first received by the early visual system, their effects are assumed to be very brief; the activity in the participating cortical columns decays rapidly unless higher-level processes contribute additional activation. Without the additional activation, further processing does not occur, unless the processing has become so routine that it is automatic, i.e., not requiring attention. When processing from one site to another in the system is automatic, the required activity is presumed to be at a low level and of very brief duration. In contrast, when processing is attentional, the activity in participating sites is relatively high and the duration relatively long-lasting.

The higher-level processes, which control the returned activation to the preattentively activated sites, are themselves influenced by motivational factors. The duration and intensity of my attention to the person with the raised hand or the person with the red coat depends upon their interest to me. The matter of motivational "interest" in the object is important to the assumption that the control of attention lies in the frontal areas, because the brain structure which is assumed to mediate motivational "interest" in an object, the basal ganglia, projects its influence to the frontal cortex, and not to the posterior cortex (see Figure 2). Therefore, to enable our interest in an object to influence our attentional expression to it, the frontal cortex would appear to serve an intermediary role, and that intermediary role is assumed to be the control of intensity and duration of the posterior cortical expression of attention.
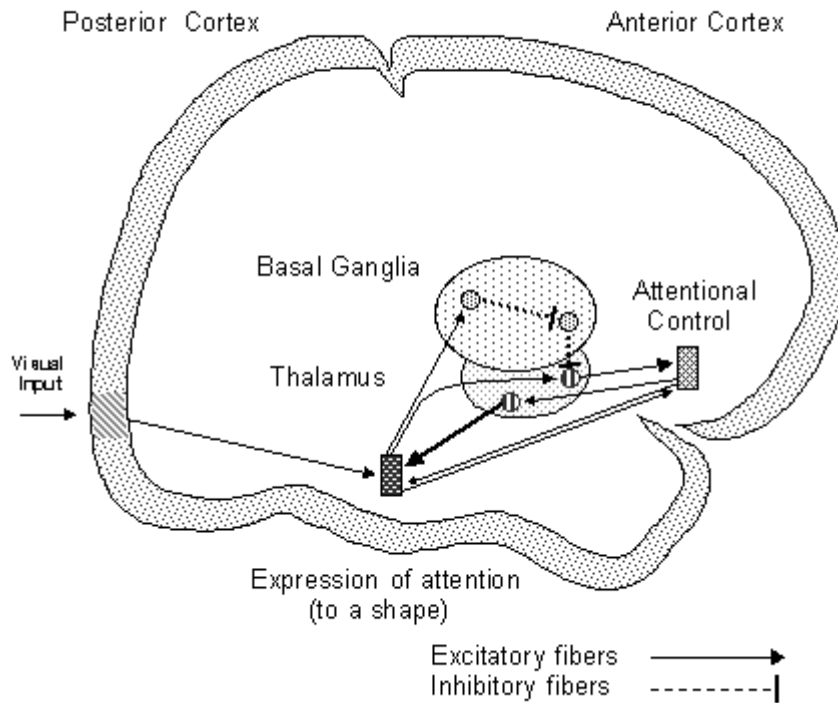
Figure   **2**
Motivational control of the triangular circuit. Two reciprocal triangular circuits represent bottom-up and top-down flow of signals from an expression of attention in the posterior cortex to a control of attention in the anterior cortex. The output from the basal ganglia tonically inhibits the bottom-up triangular circuit's indirect route through the thalamus, but this inhibition is blocked if the object of attention (coded in the site of attentional expression) activates neurons of the basal ganglia, representing a motivational interest in the object. Blocking of basal ganglia inhibition of the thalamus allows the columns of attentional control to be activated by bottom-up signals, and to respond by continuing to activate the source of these bottom-up signals in the site of attentional expression. Signals flowing in this loop of two triangular circuits thereby prolongs the attentional state.

1.5. The Value of Two Connections (Within the Triangular Circuit)

In Section 4 of his commentary, Cave asks for justification of the assumption that the two connections within the triangular circuit serve different and necessary functions in attention. This question deeply probes the boundary separating the triangular circuit theory from traditional cognitive theories that express their assumptions solely in terms of information-based concepts. The triangular circuit is assumed to connect one cortical site (clusters of columns) with another cortical site by two routes: a direct connection and an indirect connection via the thalamus. The direct connection may be considered an *informational* connection and the indirect connection a *modulatory* connection. The direct informational link typically operates at low activity levels and with very brief

durations; therefore it is suitable for carrying out the routinized, automatic processes that constitute the "9/10 of the iceberg" of cognitive processing. The indirect modulatory link typically operates at moderate activity levels and with durations that are brief to prolonged (but almost always longer than the very brief durations in the direct, informational connection). Therefore it is suitable for carrying out attentional processing evoked by novel situations, in which additional activity is required to send signals along new and less traveled routes. Thus, top-down direct connections mediate automatic processing, while top-down indirect connections (involving thalamic enhancement) mediate attentional processing.

The concept of a "modulatory connection" is tied to the concept of "activity" in cortical columns (LaBerge, 1998), because operations which change levels of activity are called modulatory. The concept of "modulation of activity" is not found among the cognitive operations performed on a stimulus input, e.g., the operations of transformation, filtering, decision, storage, retrieval, and use in producing actions (what is the implication of increasing the voltage of the bits registered at a particular computer address?). However, the notion of "increased activity" in cortical columns could be used to account for: (1) the expression of attention at a cortical site, in which the activity at the attended site is greater than the activity at the surrounding sites (see the reference article, 1997, pp. 153-159), (2) the speeding of response time when one has engaged in anticipating the triggering stimulus (e.g., LaBerge, Auclair, & Sieroff, 2000), (3) the protection of processing from intrusion of distracting events, (4) the amplitude variations obtained directly from brain imaging, and (5) the "stuff" of immediate experience.

Cave points out that while the bottom-up triangular circuit typically operates in one (feedforward) direction, the typical top-down triangular circuit operates as a (feedback) loop between prefrontal and temporal (or parietal) areas. Why then is there any need for the direct connection between the prefrontal area to the temporal (or parietal) area? Again, I would answer that the direct connection mediates top-down automatic control. This route is faster and carries low-voltage (association-like) information (see the reference article, 1997, p.171), which is used to carry out automatic tasks, (e.g., reading), rapid automatic visual scanning of an image one's living room, and converting abstract memory codes of words in sentences into perceptual images. In these examples, the direct connections allow fast elaborative associations (e.g., is there something to be feared in these images), and we often find ourselves acting on these associations before attention catches up and provides a more complete and vivid image.

1.6. The Pyramid Processor of Tsotsos: Selection by Suppression

Tsotsos confines his comments to the problem of selection in two situations: the way the visual system selects a single displayed stimulus out of inevitable neural noise when bottom-up mechanisms operate alone, and the way the visual system selects one of two displayed stimuli when both bottom-up and top-down mechanisms operate together. He provides a set of drawings which graphically illustrate how a simple winner-take-all

(WTA) mechanism solves the problems of eliminating noise from internal sources and from external sources (a distractor) so that the dominant output to higher levels of the system consists of the only signals coding the attended object. Because the visual system is wired with extensive interconnections between columns at every hierarchical level, signals arriving at one set of columns are distributed across neighboring columns (as opposed to a parallel segregated wiring scheme in which there is no cross-talk between columns, producing strict local coding of stimulus inputs). The consequence of this interactive network is that the initial coherence of signals from an incoming stimulus will be degraded more and more as the signals progress upward through the hierarchy of the visual system. Effectively, the signal-to-noise ratio of a input stimulus is decreased as it penetrates the system. This detrimental effect, due to neural contexts, is termed the "routing problem" and is a general problem facing a large class of networks, neural and non-neural. It would be a neat accomplishment if the solution to the routing problem also solved the selective problem in both preattentive and attentive processing.

Before responding to the structural characteristics of the WTA model, it may be illuminating to ask what the WTA model does for visual processing. Preserving the coherence of a signal pattern against the infiltration of surrounding noise, first of all, would promote the *segregation* of that object from other objects. But the ongoing processing necessary to insure the continued segregation of several displayed objects does not constitute a condition for selection of one of those objects, by either preattentive or attentive processes. Preattentive selection of an object in a cluttered field is typically produced by its abrupt onset (e.g., blinking it on and off), or by imbuing it with an attribute which is unique among the other objects (e.g., coloring it red and the other objects blue). Suppose that four widely separated people in the classroom raise their hands at the same time. The WTA mechanism assures that the four hands will be segregated from their immediate surrounds at the output level of the visual hierarchy, and it also provides higher output activity for the four hands relative to the other bodies in the room. However, it does not provide for what happens next, which is the directing of attention to one of the hands (or a quick scanning of one hand after another). Attention implies the existence of some other mechanisms that do the job of directing top-down activity to one particular hand, which increases and sustains the activity initiated by the abrupt onset event of raising the hand. If a particular hand (e.g., belonging to someone you have wanted to hear from) is raised, then attention is prolonged to this hand's location and we gesture for the person to speak. The mechanism which prioritizes object/locations involves much more than the WTA mechanism, which selects only by suppressing noise in the surround.

When selection of one object among many objects involves top-down attentional processes (instead of involving only bottom-up preattentive processes), there are selection mechanism operating also in the frontal areas, where objects are coded in other "maps", and the selective process may not operate in the same way as it does in the hierarchically organized network of the posterior cortex. Selection within the frontal cortical maps involves competitive processing among the objects coded there, and this competition is strongly influenced (via the thalamus) by the motivational values of perceived objects coded within a basal ganglia map (see Figure 2), in which objects and

their affective values have been associated (presumably by classical conditioning). Thus, when a set of objects which are initially selected by a pre-attentive, bottom-up mechanism (e.g., the WTA mechanism of Tsotsos), one of the objects is subsequently selected by a top-down mechanism for attention only if it is of interest to the system.

In his Figure 2B, Tsotsos acknowledges the existence of top-down selection of one of the two stimulus inputs by adding a top-down input unit above the output layer of the visual processing pyramid, and says that attention is focused at the location of the output layer corresponding to the location of the selected input." But, the set of operations at higher-levels of the system which result in the choice of that particular object (and not the other object) is not spelled out. It is those sets of operations which are of main concern to the triangular circuit model.

Thus, it appears that the WTA model described by Tsotsos applies only to preattentive segregation and selection, and not to the attention process itself. According to the definition and description of attention given by the triangular circuit model, attentional processing begins *after* stimulus inputs have undergone preattentive segregation and selection.

Tsotsos apparently misunderstands where the "control" of attention resides in the triangular circuit model. In the second paragraph of his Section 4, he states that the thalamus is assumed to be the attentional control center (ACC) in the triangular circuit theory. But, in the first paragraph of the target article (1998) it clearly states that the control resides in "clusters of neurons in the frontal cortex".

In several places within his commentary, Tsotsos indicates that the routing problem and its related complexities of dealing with distractor noise are ignored in the triangular circuit theory. His claim is correct in the limited sense that selection in early visual processing was not addressed in either the target (1998) or reference (1997) articles. Owing to the limitation of space and particularly to the aim of emphasizing the global characteristics of the theory, I omitted a detailed description of how the thalamocortical circuit serving cortical column clusters (in frontal sites of attentional control as well as in posterior sites of attentional expression) can operate to produce selection by both suppression and enhancement. The thalamocortical circuit (shown in Figure 1) is a more local circuit nested within the larger triangular circuit, and involves a feedback loop between the thalamic relay neuron and its target cortical column (as well as reticular nucleus neurons which provide feedback inhibition and interneurons which provide feedforward inhibition). The full description of this more local circuit is given in other publications (LaBerge, 1995, 1999b, 2000). In particular, the operation of this circuit was simulated for a stimulus input display in which a target object was located between two closely-spaced distractors (LaBerge, Carter, & Brown, 1992). The trajectories of activation following the onset of the stimulus display showed both enhancement at the target site and suppression at the distractor sites (under certain parameter settings, the circuit functions in a winner-take-all manner). Therefore, the thalamus-to-cortex connections shown in figures of the triangular circuit model should always be understood to imply the existence of the thalamocortical loop, along with its function of selective

enhancement of the attended site and suppression of surrounding sites. Since the thalamocortical circuit operates from the bottom-up as well as the top-down direction, it also serves to preattentively segregate and select stimulus objects. One global difference between the thalamocortical selection mechanism and the WTA mechanism of Tsotsos is that the WTA mechanism is applied to an input at each of the several levels of the (early) visual system, while the thalamocortical mechanism is described as operating once, at one particular level of (early) visual processing. It is anatomically more realistic, in view of cellular recording and brain imaging evidence, to include several levels of early visual processing when modeling the preattentive selection processes. But, owing to the intimate connections of cortical columns with thalamic nuclei, it seems appropriate to include the thalamocortical loop along with lateral cortical connections in a model of preattentive selection.

2. Functions of the Triangular Circuit in Attention

2.1. Attentional Selection by Excitation, Inhibition, or Both?

In Section 5 of his commentary, Cave highlights a persistent problem that arises whenever we attempt to give neural accounts for behavioral effects in selective attention tasks. If behavioral data show an improvement (e.g., a reduction in response time or error rate) when a particular object is attended (compared to when it is not attended), then we attribute some kind of facilitatory effect in the neural processing of the attended object. But, as pointed out in the reference article (1997, p 154, and Figure 1), the neural expression of facilitation at the attended site as elevated activity may be produced in more than one way: by an increase in activity at the target site, a decrease in activity at the surrounding distractor sites, or both. An activity increase in cortical columns is assumed to be produced by excitatory input fibers and an activity decrease is assumed to be produced by inhibitory inputs (see Figure 1). But, it should be kept in mind that a decrease in activity in a cortical column can also be produced by a *decay* in excitatory input (reference article, 1997, p 157). This alternative way of decreasing activity at distractor sites is crucial for a top-down account of both behavioral data (e.g., Cepeda, Cave, Bichot, & Kim, 1998) and cellular recording data (e.g., Moran & Desimone, 1985) that show attentional selection occurring by the reduction of activity at distractor sites, because long-range axons that connect remote cortical areas, without known exception, are excitatory.

In his commentary, Cave describes a Feature Gate model, which uses inhibitory connections between local sites coding for color to account for selection of the location of a target color during a color search task. Desimone and his colleagues (Desimone, Wessinger, Thomas, & Schneider, 1990) describe two other models based on local inhibitory connections, which are intended to account for reduction in activity at cortical distractor sites of the monkey during selective attention tasks. The triangular circuit theory gives a contrasting account of these data, based on top-down excitation of the target site and local inhibition of close distractor sites through the reticular nucleus in the

thalamocortical circuit (LaBerge, Carter, and Brown, 1992). However, when the target-distractor distance is so large that corresponding sites in the reticular nucleus no longer influence each other, then a decrease in activity in distractor sites is accounted for by decay in top-down excitation to the distractor sites. LaBerge, Auclair, & Sieroff, (2000) describe in more detail how local inhibition of distractors can be produced within the prefrontal cortex, where widely separated locations in the visual field (e.g., locations in opposite hemispheres) are coded within a relatively small area of cortex within one hemisphere (e.g., Funahashi, Bruce, & Goldman-Rakic, 1989). Stored in these frontal control sites are records of recent target and distractor events. When a warning signal or cue begins a trial, the activities in these frontal sites excite corresponding sites of the posterior cortex where attention is expressed. The process of selection then operates on these initial levels of activity within the frontal sites to produce a higher level of activity at the target (attended) site, and a lower level of activity at the distractor (unattended) site (which is the expression of selective attention). After a sufficient number of trials, the activity levels in the frontal target and distractor sites approach a maximum (an asymptote), so that subsequent selective processing cannot occur by increasing activity at the target site, but only by reducing activity at the distractor site. This reduction of activity at the frontal distractor site occurs by inhibition from the target site (based on additional target activity due to instructions or a cue); this inhibition may occur by both cortico-cortical inhibitory fibers and/or through the thalamocortical circuit joining one frontal column cluster to another. As the activity in frontal distractor sites is inhibited, signal activity in the connections between the frontal distractor sites and the posterior cortical distractor sites *decays.* Meanwhile, the activity in the frontal target site remains constant, and the signal activity in the connection between the frontal target site and posterior cortical target site also remains constant. Hence, the trajectory of activity level of the target and distractor within columns of the posterior cortex show an initial rise to a high level when the trial begins, and then the activity level at the distractor site decays while the activity at the target site remains constant. This trajectory pattern in posterior cortical sites coding for the target and distractors describes the pure case of selection by decreasing distractor site activity. Cases in which selection combines a decrease in distractor site activity with an increase in target site activity presume that frontal storage of recent distractor and target events were not at maximum capacity, or that frontal control received additional attentional influences, for example from instructions to attend strongly on a particular trial (LaBerge, Auclair, & Sieroff, 2000).

This description of top-down controlled selective attention, based on the triangular circuit theory, appears to resolve the problem of the "enigma of cognitive inhibition", presented by Cowan in Section 2 of his commentary. Cowan separates "spreading inhibition" from "specific inhibition". Spreading inhibition appears to refer to local inhibitory effects, for example, effects between closely neighboring cortical columns or between corresponding sites within the reticular nucleus. Specific inhibition appears to refer to inhibition of a site which is directly controlled, rather than an indirect effect of the control of another site, such as a target site. According to the triangular circuit view, specific inhibition is really decay of top-down excitation, not a global, long-range type of inhibition, because long-range inhibitory fibers joining remote cortical areas apparently do not exist. As an example of a task which demonstrates specific inhibition, Cowan refers to negative

priming. The negative priming effect (e.g., Tipper, MacQueen, & Brehaut, 1988) is described as the increased in response time to a target item on a given trial when that item was a distractor on the previous trial. The present top-down account of the triangular circuit theory assumes that the occurrence of the target item as a distractor on the previous trial decreased activity at its frontal control site, owing to the selection process which inhibited this particular object. Then, at the onset of the following trial, its lower activity increases the time required to process it as a target (i.e., to produce an appropriate difference between the target site activity and distractor site activity) in the frontal sites, and hence the response time will be increased over the control condition.

Cowan questions the ability of the triangular circuit theory to account for data from object permanence tasks, in which infants gradually learn to inhibit a dominant response (Diamond & Gilbert, 1989). The problem, as he sees it, lies in the assumption of the purely excitatory direct action of the prefrontal cortex." But, if the prefrontal cortex contains sites corresponding to location and attributes of objects, and if these sites are located more closely here than they are in the posterior cortex maps, then local inhibitory connections within the frontal cortex can operate more effectively here to manipulate control of attention in these tasks.

2.2. How Does the Triangular Circuit Theory Account for the Neglect Syndrome?

This question, posed by Cowan in Section 1 of his commentary, is tied to the more general issue of the special role of the parietal lobes (compared with the occipital and temporal lobes) in attention. The parietal lobes are special because they express attention to location, and the location of the attended area enables selective processing of objects in the external world including the selective processing of parts of our bodies. When abrupt onsets occur, activity is registered in the parietal sites and sent on to frontal control sites, which may or may not return additional activation to the parietal sites. I regard the registration of activity of one or more stimuli in parietal sites as "orienting", while the addition of activity returned to one site from frontal control I regard as "attention" (LaBerge, 1999a, 1999b). If a lesion destroys the mapping in the parietal lobe of one hemisphere, then this hemisphere cannot send activity to the frontal control area to compete with activity from the other hemisphere map, and therefore, when objects appear in both the contralesional and the ipsilesional fields, the control site activates only the ipsilesional object location via the triangular circuit. If, instead, there is a lesion in the pulvinar nucleus of the thalamus, then the top-down triangular circuit involving this thalamus cannot amplify the activity projected (by the direct route of the circuit) to the contralesional parietal site, and response times will be slowed (Rafal & Posner, 1987), but not as much as when the lesion is in the parietal site, where attention to location is expressed. When an object appears in only the visual field contralateral to a parietal lesion, its shape and attributes can be processed through the intact contralateral occipital and temporal lobes, and in this way an effective response usually can be made to the object. Processing through the contralesional "what" pathway apparently occurs even

when objects are presented in both fields simultaneously: Volpe, LeDoux, & Gazzaniga (1979) showed that parietal patients could make accurate same-different judgments of objects presented in the intact and neglected fields, while failing to identify objects in the neglected field.

Cowan asks how the triangular circuit theory can explain why the parietal lobes have greater role in "awareness" than temporal or occipital lobes. In the target article (1997), Section 3, paragraph 2, it is stated that "the representation of selfhood....is almost always associated with the body, and the body surface is richly represented within the cortex (Damasio, 1994)." The body landscape is mapped in the somatosensory part of the parietal lobe, and activation of the cortical columns in this area from medioventral areas of the frontal cortex (through a triangular circuit) provides the main expression of attention to the self. Hence, the parietal lobe is special, not only because it enables attention to spatial location but also because it is crucial for attention to the self, and therefore to the expression of "awareness" as defined by the target article (1998) and the reference article (1997).

2.3. Distractions and Shifts of Attention

In Section 3, sentence 2, Cowan states that I "reasoned that events that interrupt voluntary attention do so only infrequently ...". This statement arises from a misreading of the relevant text on pages 164 and 165 of the reference article (1997). Nowhere is it stated or implied that events that interrupt voluntary attention are infrequent, in everyday life or in laboratory tasks.. Possibly, this incorrect inference occurred when reading the sentence "It is rare that external stimuli are strong enough to prevent voluntary attention from overriding their effects." The main point of this section of the reference article (1998) is that top-down activations possess the necessary *power* to compete successfully with almost all external stimuli; the text did not suggest that external stimuli provide guidance for attention only infrequently. Actually, my interpretation of the triangular circuit theory is in agreement with Cowan's claim that external stimuli and internal controls work together in most cases of attention to everyday sensory objects and events.

2.4. The Subjective Distinction Between Percept and Image

Cowan's Section 4 commentary appears to converge on the problem of finding experimental indicators of the commonly held impression that people can almost always distinguish their internally generated images from externally driven perceptions. I agree that such a phenomenally clear distinction should find objective support from appropriate experimental indicators. Perhaps a consideration of brain substrates of expression of images and percepts could suggest some new experiments. Both percepts and images are attentionally driven, according to the present theory, but the expressions of a percept and an image would appear to involve different distributions of activity levels over the

relevant posterior cortical sites. Activation of an image of an object, for example, the Washington Monument, would seem to begin with activation of the whole shape, which involves oriented edges and surface features. The cortical sites representing these aspects range from IT to V4 to V3 or V2, with decreasing activity levels. Area V1 might be indirectly activated through one of these other areas, and if so, probably only very weakly. Thus, the image of the whole monument would seem to activate later visual areas more strongly than earlier visual areas. In contrast, activation of a percept by incoming sensory signals, activates V1 strongly and successive levels somewhat less strongly. Thus, the impression of brightness, which is coded in earliest levels of the visual hierarchy, would be stronger in a percept than in an image, and brightness seems to be a prominent feature by which a percept is subjectively discriminated from an image.

3. Relations of Attention to Awareness and Self-Awareness

3.1. The Confusion of "Awareness" with "Consciousness"

Cowan and some of the other commentators apparently resisted the definition I proposed for "awareness" in the target (1998) and reference (1997) articles so much that they overlooked it and so whenever the word "awareness" appeared in the text, they interpreted it in the traditionally received way as "consciousness" or as some form of "consciousness". The second sentence of Section 3 of the target (1998) article states: " A main goal of this paper is to forge a clear concept of "awareness" in the brain not by attempting to distinguish it from "consciousness", but rather by defining it with concepts described in the earlier part of this paper". It is possible that the first part of this statement may have conveyed the impression that "awareness" was not to be distinguished from "consciousness" in the sense that they were to be considered synonymous. But the second part of the statement makes clear that awareness will be defined with concepts described in the earlier part of the paper, and consciousness was *not* one of the concepts described in the earlier part of the paper. Also, the next sentence would appear to eliminate possible ambiguity when it specifically describes awareness in terms of attention: "Specifically, an event of awareness is conjectured to involve (a) the operation of attention (b) which is directed toward a representation of the self." I considered inventing a new word, but rejected that alternative for two reasons: (1) I considered that word "awareness" had often been used in literature in the sense of an elevated mental state that involved the agent as part of its content, and (2) it seemed a waste of semantics to let the word "awareness" continue to serve as a synonym of the word "consciousness" which is almost useless, owing to its many current meanings. Therefore, instead of starting with the vague concept of consciousness and attempting to analyze out awareness as some aspect of it, I started with what I considered a well-formulated concept of attention, and then added something well-formulated to it (the bodily sensations mainly), and labeled this combination the "awareness" property.

3.2. Eye Movements and Attention: Clarifying the Assumptions of the Triangular Circuit Theory of Attention

Fischer's commentary examines carefully the relationship between an active triangular circuit in the brain and the events of attention and awareness. The circuit he examines is located within the oculomotor system and produces voluntary saccadic movements of the eyes. The control site is in the frontal area (presumably the frontal eye fields of Area 8), and there exist direct connections from it to the tectal area (containing superior colliculus neurons which activate the oculomotor nuclei that drive the eye muscles), and indirect connections with the tectum via the parietal area. He describes two experimental tasks which he claims involve not only attention but awareness, and claims that under some conditions voluntary saccades occur without attention (or awareness), because subjects sometimes fail to report these eye movements. In such cases, he maintains, the brain is aware (because the triangular circuit that controls the eye movements has been activated), but the subject is unaware of the saccades.

Saccadic eye movements, like movements of breathing, allow voluntary as well as involuntary control. In Fischer's first experiment, subjects are induced to make voluntary saccades by moving the eyes in the direction opposite to the location of the stimulus. The subjects made many errors, but failed to report about 50% of them, even though about 98% of the errors had been corrected. In the second experiment, subjects watched a stimulus change orientation at the rate of about 6 frames a second (about 167ms per frame), and reported the orientation of the last orientation before the stimulus disappeared. Again, subjects showed a discrepancy between their actual performance and their report of their performance. Fischer interprets these discrepancies as evidence that a triangular circuit had been activated without producing awareness in the subject.

There are three issues addressed here which probe the boundaries of the basic assumptions of the triangular circuit of attention and its application to awareness: (1) can any triangular circuit in the brain support attention? (2) can any activity generated by a triangular circuit qualify as attention, even when it is very brief in duration? (3) does a voluntary movement of the body (e.g., a voluntary saccadic movement) necessarily qualify as attention to the self, because the target of the controlling circuit involves the body?

The frontal-parietal-tectal circuit in the oculomotor system produces a saccadic eye movement that is planned and executed in a fraction of a second (about 250 ms). We make about five of these movements every time we read a line on a typical page of print. Even if we instructed ourselves to read (voluntarily) only every other word along a line of print, the duration of activity in the planning component of a saccadic eye movement is brief, just long enough to program the even briefer movement trajectory. The activity in the tectum that produces the movement is a triggering activity, which is over quickly, allowing for new activity to produce a new movement. There is no time for feedback from the activity of the tectal neurons to the origin of control to sustain activity there. The

signaling in the tectum is a rapid in-and-out operation. In contrast, brain sites where attention is expressed do not serve merely as relay stages whose purpose is only to send signals to the next stage. The "relay" neurons of the thalamus were so named when the thalamus was regarded merely as a place where incoming sensory impulses crossed a synapse en route to a cortical projection area. But a better term is "relais" neuron ("relais"also means a French country inn), which suggests that signals that arriving in the thalamus do not immediately depart, but stay in the thalamo-cortico-thalamic loop for awhile, and make themselves at home.

What is attended during the planning of an eye movement is almost always the image of the terminal state of that movement, which is a location in visual space, coded in parietal lobe. So, the expression of attention of an eye movement is in the parietal area, not in the tectum, which serves to relay signals to the oculomotor muscles. In some cases of parietal activations, e.g., while rapidly reading successive words on a page, the durations are so brief that there is no time to return activations to the frontal control area. Many would label this type of selective activity as automatic, (i.e., not attentional), and maintain that what is being attended is some ideational output of the comprehension process. Like activities that mediate eye movements, automatic cortical activities are almost always brief in duration. Therefore, my answer to (1) is that the triangular circuit involving an image of the terminal point of an eye movement consists of the frontal, parietal, and pulvinar areas, and not the tectal area, which mediates motor signals to the eye muscles. My answer to (2) is that the duration of parietal activity at the location opposite the stimulus in Fischer's experiment may sometimes not be sufficiently long to qualify as an attentional event (that is, the processing on some trials may be automatic).

The third issue (3) is whether or not a voluntary movement of the body (e.g., a voluntary saccadic movement) necessarily qualifies as attention to the self, because the target of the controlling circuit involves the body? Are Fischer's subjects attending to themselves as an actor every time they make a saccade in a direction opposite to the stimulus (i.e., an antisaccade)? Attending to oneself is assumed to involve attention to the bodily landscape, in the sense that Damasio (1994) regards the bodily landscape as sensations of the body as a whole, not as a specific part. When I move my finger along a line on a highway map, I may attend to my bodily landscape if the map is telling me that I will soon be driving on a narrow mountain road, but I will probably not attend to my body landscape if I am simply looking for the place where two highways intersect. Also, the actor does not seem to be involved when the subject attends to a terminal point of an impending eye movement, because it is the visual location in the parietal lobe that is typically activated, not a kinesthetic image of the new eye position. However, on some occasions when an error is made in Fischer's tasks, the subject may react with bodily feelings that are attended for a second or two. At these moments, on my view, the subject is very much "aware".

3.3. When is Processing Automatic, When is it Attentional, and When is it an Event of Awareness?

Tzelgov presents an alternative set of criteria by which a cognitive process is categorized as being either automatic or an event of awareness. Thus he merges the categories of attention and awareness by considering them both to be cases of nonautomatic processing. My category of the "object attended circuit" he regards as automatic processing, and the "self attended circuit" he expands to cover all nonautomatic, attentional events. The defining property of awareness for him is the event of *conscious monitoring,* which he defines as "the intentional setting of the goals of processing and intentional evaluation of its outputs". Monitoring involves symbolic representations, which are regarded as the output of psychological processing (as opposed to subsymbolic components characteristic of other biological processes). Thus, on this view, considerable additional cognitive processing characterizes the nonautomatic event, while on my view this event is characterized simply by activated triangular circuits (having some minimum duration). In Section 4 of his commentary, Tzelgov uses the example of reading the word "red" by a bilingual person who has never seen the word before in her second language. He assumes that the processing of the word is monitored, and therefore evokes awareness, while my view (contrary to his statement of it) is that the processing of the word involves attention to visual and semantic processing, but does not necessarily involve attention to the self (the feeling of the body landscape or verbal descriptions of the self); the reader may know that "the read word means red", while the self remains unattended.

Therefore, while I attempt to separate automatic processing, attentional processing, and processing with awareness in terms of the presence or absence of activity in triangular circuits, Tzelgov uses conscious monitoring, which he describes in terms of symbolic representations that are either evocative (having "less than propositional form") or deliberative (having propositional form). There is not space here to provide an adequate critique of this alternative way to separate automatic from nonautomatic processing, but the crucial role of representations in his characterization of monitoring nonautomatic processing is contrary to the general approach of the triangular circuit theory to nonautomatic processing. Representations are processed quickly, and there is almost always no benefit in prolonging them (we are constantly improving the processing of the computer by *shortening* the duration of its symbolic events). But the rapid in-and-out of cortical column processing contrasts with the prolonging of the activity within them, which occurs when we anticipate upcoming sensory events or actions, or when we savor sensations or feelings.

The triangular circuit theory generates a simple and clear way to distinguish automatic processing from attentional processing of the top-down kind: When only the direct route from the control site to expression site is activated within the triangular circuit, the process is automatic; when the indirect route from control to expression through the thalamic amplifier is activated, the process is attentional. When cortical columns process information automatically, the in-and-out process is fast and at low intensity; in contrast, when cortical columns process the attentional state, the in-and-out aspect of processing is relatively slow. Thus, the direct route through the triangular circuit involves fast, low intensity processing; it allows the quick resetting of control, so that processing can shift rapidly from one kind to another (as in proposition-based thinking); in contrast, the

indirect route involves slow, higher intensity processing, so that resetting of the control to process something else takes more time (as in preparing for or savoring a sensation). In bottom-up processing, the processing of a stimulus input occurs along direct routes of triangular circuits when the stimulus onset intensity is low. When the onset intensity is high, the indirect routes through the thalamus are activated and result in amplification of the stimulus input; when the resulting signal intensities reach frontal areas, they can interrupt whatever is being attended, and then compete for activation to be sent to their own sites of expression in posterior cortical sites.

3.4. Blood Flow Measures, Localization, and the Triangular Circuit

Rudell points out that the triangular model of attention and awareness "demanded a highly compartmentalized brain in which discrete brain areas performed distinct mental functions". Therefore, this model is on the side of "strict localization" against the "equipotential" view of brain function. Much of the evidence that is gathered to support the localization side of this controversy is based on measures of blood flow within the brain while a subject performs a cognitive task. Rudell presents a clear and detailed critique of current interpretations of brain imaging data and the subtraction of data between the several versions of a task within an experiment. Those of us who look to brain imaging as our major source of evidence for testing models would do well to heed his well-articulated caveats.

In the final sentence of his commentary, Rudell characterized the triangular circuit theory as being based on "a highly compartmentalized brain in which discrete brain areas performed distinct mental functions". I agree that the theory is more on the side of localization of function as opposed to equipotentiality of function, but the theory need not be based on strict localization of functions in discrete sites or "spots" of the brain. Indeed, the schematic diagrams in the figures of the target (1998) and reference (1997) articles give the impression of functions being localized discrete sites, but I plead guilty of once again simplifying exposition in the interests of communicating clearly the main ideas to the reader. In the figures of the triangular circuit, the rectangular spots representing cortical sites of control and expression should be interpreted not as strict localized coding of these functions, but rather as distributed coding of these functions. Thus the control site is actually spread more widely (but not entirely) across the frontal cortex in a distributed network, where a particular column may participate in the coding of many different cognitive items. The expression site in the posterior cortex may not be strictly localized to a cluster of columns, but may also involve activation of columns at lower levels of the extrastriate hierarchy. If a distribution of cortical columns is involved during attentional processing, then a distribution of connected thalamic neurons is involved. But, in the case of the expression of attention in posterior cortex, the activated thalamic neurons are localized to the pulvinar nucleus, while in the case of the control of attention in frontal cortex, the activated thalamic neurons appear to be localized mainly to the mediodorsal and ventrolateral nuclei.

Therefore, it would seem that, apart from the present assumptions of distributed coding within particular brain areas, Rudell is right in pointing out that the triangular circuit theory rests firmly on the assumption that the control, amplification, and expression of attentional activity in the brain take place in separate parts of the brain's architecture.

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