Perception, Action, and Awareness: A Three-Body Problem

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IN:

Relationships Between Perception and Action
Edited by O. Neumann and W. Prinz

CONTENTS

Introduction

Most chapters of the present book deal with a two-body problem, relations between perception and action. This two-body problem is difficult enough: as Miller, Galanter, and Pribram (1960, p. 11) point out, the "theoretical vacuum between perception and action" has been the subject of prolonged - and frequently violent - debate. However, two-body problems are well known to be solvable, and I myself have proposed a detailed theoretical solution to the relation between perception and action in the case of language (MacKay, 1987a) and other cognitive skills (MacKay, 1985, 1987b, pp. 14-140). The present chapter takes on a three-body problem that has proven much more difficult to solve: relations between perception, action, and awareness.

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The relations between perception, action, and awareness raise three broad classes of theoretically fundamental issues. The vicissitudes of awareness are central to the three-body problem, part 1, which includes questions such as: Why is awareness usually but not always associated with higher-level processing; In producing sentences, for example, why are low-level phonetic units normally produced without awareness but suddenly enter awareness when speakers misproduce a speech sound (MacKay, 1988)?

Differences between conscious versus unconscious processing are central to the three-body problem, part 2, which includes questions such as: Why is conscious processing so much slower than unconscious processing in perception and action; Why, for example, do subjects take so long (about 7.73 s on average) to become *conscious* of the two meanings of a lexically ambiguous sentence (MacKay & Bever, 1967), when available evidence indicates that both meanings have been processed *unconsciously* 300 ms after arrival of the ambiguous word (Swinney, 1979)?

Relations between awareness, attention, and practice (repeated retrieval) are central to the three-body problem, part 3, which includes questions such as: (a) Why do we normally become conscious of what is new in perception and action, while what is old or frequently repeated drops out of awareness, as in habituation and automaticity (Shiffrin & Schneider, 1977); (b) Why is practice essential for carrying out several perceptual and motor activities simultaneously, so that subjects can speak and play the piano concurrently without mutual interference, for example, but only after extensive prior practice (see Allport, 1980); (c) Completing the circle, why does action have such profound effects on attention and awareness; When subjects respond to an input arriving via one channel, for example, why is awareness of a target arriving simultaneously on another channel greatly attenuated (Ostry, Moray, & Marks, 1976)?

Structure of the Chapter

This chapter develops a detailed and explicit theory of attention and awareness in perception and action and divides into five sections. The first section describes the stages of development that the theory has already undergone and provides a preview of subsequent sections. The second section describes the theoretical foundation available when I began this chapter, the node structure theory of relations between perception and action. Included in this section are the basic processes in the theory (e.g., priming), the mechanism for activating nodes, and a general principle (the principle of higher-level activation) that determines what nodes become activated during perception. Because I have outlined the empirical and theoretical underpinnings of these basic processes elsewhere, the second section will present theoretical assumptions as if they were established facts, and will introduce theoretical terms without going into their rationale. Please follow closely as I lay out these theoretical building blocks because we will need them later in our discussion of attention and awareness[1].

The third and fourth sections show how awareness and attention can be incorporated into the theory outlined in the second section, and the fifth section shows how the extended theory applies to the three-body problem, the basic phenomena that any theory of relations between perception, action and awareness must address.

The Node Structure Theory: History and Prospects

Three stages of theory development have preceded the present paper. Some curious differences between the rate of producing internal vs. overt speech (MacKay, 1981) provided the original impetus for stage 1 of the theory. Stage 2 (MacKay, 1982) extended the theory so as to address more general issues: errors in action, the mechanisms underlying sequencing and timing in behavior, effects of practice on behavior, and speed-accuracy trade-off in skilled behavior. Stage 3 of theory development (MacKay, 1987a,b, 1990) added perception to the theory, including the perception of ambiguous inputs, relations between errors in perception and action, asymmetries in the ability to perceive vs. produce skilled behavior, the role of feedback in the perceptual monitoring of skilled behavior, and the effects of delayed and amplified auditory feedback on the production of speech and other cognitive skills. The node structure theory, stage 3, therefore addresses a wide range of phenomena, including the full scope of knowledge about relations between perception and action, and, because of its scope, the theory requires a sizeable number of assumptions.

The present paper outlines the node structure theory stage 4, an account of attention and awareness, and the remainder of this section previews this extended theory and how it bears on the three-body problem. The main addition to the theory is "pertinent novelty," which refers to a novel conjunction of internal or external events that fall into familiar categories or domains. Pertinent novelty triggers orienting reactions, awareness, and commitment learning, the process whereby new connections are formed. However, newly formed connections decay over a relatively brief period, so that nonrepeated events, e.g., most sentences, receive only temporary representation. This process of connection formation and decay is shown to be consistent with available data on amnesia, including the pattern of sparing and deficit in "hippocampal patients."

Explaining selective attention will require only mechanisms that are essential for other purposes in the theory: the "most-primed-wins" activation principle, and the mechanism that engages the activating mechanisms for systems of nodes representing one source of input rather than another. Although this second mechanism

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[1] Readers interested in empirical support for the theory or in comparison with other theories such as those of McClelland, Rumelhart, and the PDP Research Group (1986) should consult the more extensive discussion in D.G. MacKay (1985, 1987a,b).

often determines what particular contents enter awareness, e.g., enabling the activation of target inputs instead of distractor inputs in selective attention tasks, the mechanisms for attention and awareness are nevertheless conceptually distinct in the theory.

Divided attention will likewise require no new "attentional mechanisms" if prior learning has established separate domains of nodes for the concurrent activities. However, if concurrent activities share nodes in the same domain, the theory predicts varying degrees of interference depending on the type of shared node (content, sequence, and timing nodes), on their temporal pattern of activity, and on the nature of their interconnections.

Finally, the theory will provide new insights into the three-body problem and its subsidiary issues discussed above. By way of preview, part 1 of the three-body problem (vicissitudes of consciousness) reflects the nature of pertinent novelty, the factor that triggers awareness in the theory. For example, errors represent instances of pertinent novelty, and hence can give rise to awareness of units that would otherwise be processed unconsciously. Part 2 of the three-body problem (differences between conscious versus unconscious processing) reflects the nature of the mechanisms underlying conscious versus unconscious processing in the theory: unconscious processing involves priming, a parallel and therefore rapid process, whereas conscious processing involves not just activation, a sequential and therefore slow process, but prolonged activation, an even slower process. These same mechanisms will also account for part 3 of the three-body problem (relations between awareness, attention, and practice). For example, awareness of inputs to unattended channels is attenuated during response to a target on an attended channel because responses require most-primed-wins activation mechanisms that are either-or in nature.

Basics of the Node Structure Theory of Perception and Action

The basic components of the theory are nodes, which are hypothetical processing units (as in Wickelgren, 1979) that share a set of relatively simple structural characteristics and processing capabilities, and respond in the same way to variables such as practice (repeated activation). Unless otherwise specified, the nodes discussed in the present paper play a role in both perception and action (see also Prinz, this volume). These "mental nodes" represent neither sensory input nor patterns of muscle movement, but higher-level cognitive components common to both perception and production, e.g., segments and syllables at the phonological level, and words and phrases at the sentential level. Mental nodes become active when we perceive a word (or sentence) and when we produce it, either aloud, or within the imagination (internal speech). During perception, including perception of self-generated feedback, mental nodes receive "bottom-up" inputs from sensory analysis nodes that represent patterns of, say, auditory input arriving via the basilar membrane and associated auditory pathways. During production, these same per-

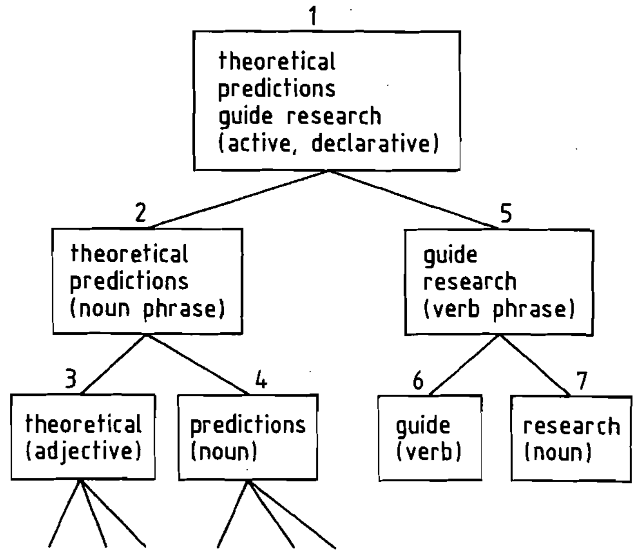

Fig. 1. The top-down hierarchy of nodes for producing the words in the sentence "Theoretical predictions guide research." The *numbers* represent the order in which the nodes become activated during production

ception-production units send "top-down" outputs to muscle movement nodes that represent patterns of movement for the speech muscles, producing contractions of respiratory, laryngeal, velar, and articulatory muscles.

Hierarchic Connections Between Nodes

In general, connections between nodes are "partially hierarchic" rather than "strictly hierarchic" (see MacKay, 1987b, pp. 17-22), but this distinction is not important for present purposes, and Fig. 1 illustrates the simpler case, a "strict hierarchy" of top-down connections between sentential nodes for producing the sentence, "Theoretical predictions guide research." Following MacKay (1982), I designate each node by a two-component label (see Fig. 1): the content that the node represents appears in italics, followed by its sequential domain (explained below) in brackets. For evidence supporting the particular units and connections illustrated in Fig. 1, the reader is referred to MacKay (1972, 1973b, 1978, 1979, and 1987b, pp. 14-38), and Treisman (1983). Omitted from Fig. 1 are the phonological nodes and the complex but otherwise similar hierarchy of nodes underlying the control of muscle movements.

Processing Characteristics of Nodes

Nodes exhibit three processing characteristics that are necessary for understanding awareness in the theory: activation, priming, self-inhibition, and linkage strength. Awareness itself arises from a fourth processing characteristic (prolonged activation) discussed later.

Node Activation

I use the term "activation" as short for "node activation" in the remainder of this chapter, and the reader is asked to keep in mind the following differences between node activation and other current uses of the term "activation" in the cognitive and neural sciences (see MacKay, 1987b, p. 9). Node activation is necessary for conscious perception and action and is all-or-nothing in nature: the intensity of node activation never changes with "distance," fatigue, or the number of other nodes connected to an activated node. Node activation is terminated by a period of reduced excitability called self-inhibition (discussed on p. 275) and is self-sustained until then: node activation lasts for a specifiable period of time, regardless of whether the sources that originally led to activation continue to provide input. Finally, node activation is sequential and nonautomatic in nature: a special activating mechanism must become engaged to determine when and in what order nodes within a system become activated (for an example of sequential activation during production, see the numbered nodes in Fig. 1).

Node Priming

"Node priming" refers to a transmission across a connection of subthreshold activity that spreads with decrement: an activated node primes its connected nodes most strongly (first-order priming), while an unactivated node receiving first-order priming primes its connected nodes less strongly (second-order priming), and so on up to *n*th-order (null) priming (the value of *n* being currently unknown: see MacKay, 1990). Priming prepares a node for possible activation, and all nodes must be primed in order to become activated.

Priming summates spatially (when two or more connections to the same node are simultaneously active), and temporally (during the time that any given connection remains active). However, summation of priming cannot by itself activate a node: a special activating mechanism is required for activation, and priming only accumulates to a subthreshold asymptotic level (see Fig. 2).

Unlike activation, priming does not self-sustain: it begins to decay as soon as input from its connected nodes stop. Also unlike activation, no period of self-inhibition and recovery follows priming, and no special triggering mechanism determines when and in what order nodes become primed. Indeed, priming is a parallel process: an active source simultaneously primes all connected nodes. Contrary to the usual assumption that priming in sentences is a left-to-right process (see Neumann, 1984), priming is nonsequential, and backward (right-to-left) priming can be as effective as forward (left-to-right) priming in the theory (see also Koriat, 1981).

Linkage Strength

Linkage strength is a relatively long-term characteristic of a connection that is determined by practice (the frequency with which a node has been primed and activated via a particular connection in the past). Linkage strength determines how

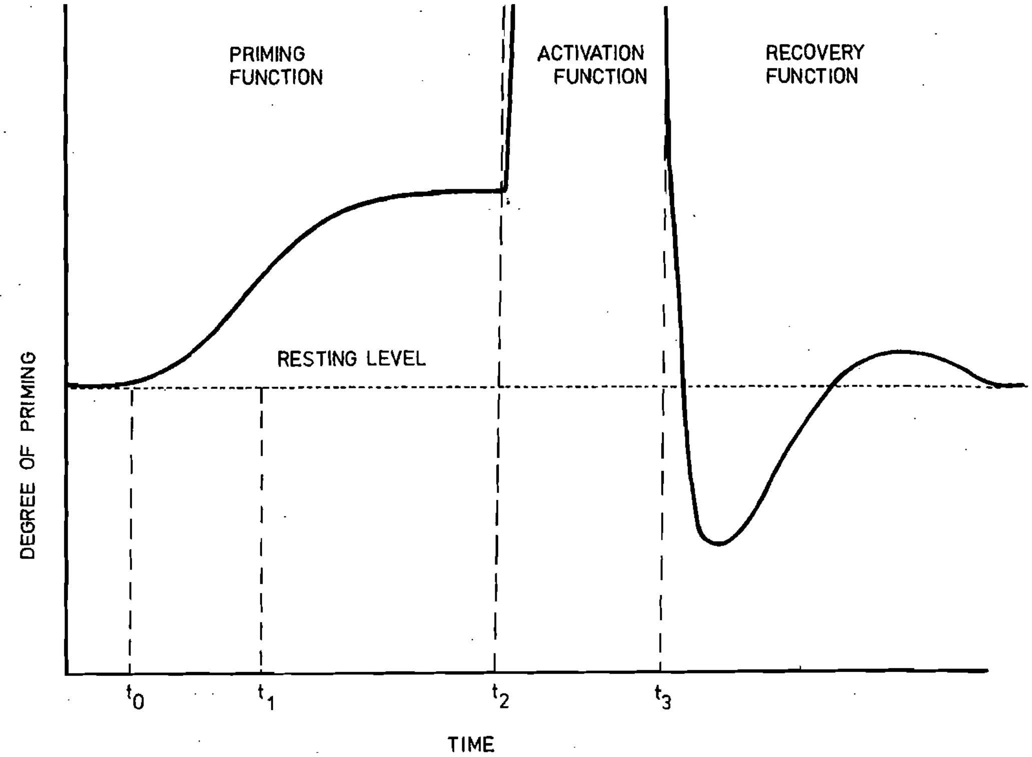

Fig. 2. The priming, activation, and recovery phases for a single node. The priming function shows how priming summates to asymptote following onset of priming at t_0. The activation function illustrates multiplication of priming and self-sustained activation until time t_3. The recovery cycle shows how priming first falls below resting level (self-inhibition) and then rebounds (the hyperexcitability phase)

much and how rapidly priming crosses a connection and is reflected in the initial slope and asymptote of a priming function: highly practiced connections transmit priming more rapidly (i.e., with a steeper slope) and up to a higher asymptotic level than do relatively unpracticed connections. These characteristics of linkage strength explain a wide range of practice effects in the psychological literature (see MacKay, 1982).

Self-Inhibition

After a node becomes activated, it undergoes a brief period of self-inhibition during which its level of priming falls below normal or resting level (see Fig. 2). The mechanism underlying self-inhibition is an inhibitory collateral or "satellite" that sends an inhibitory connection to and receives an excitatory connection from the "parent" node. After receiving sufficient first-order priming from its activated parent node, the satellite becomes activated and inhibits its parent node, which becomes deactivated, thereby deactivating its satellite and enabling recovery in the parent node to begin. Because linkage strength between the parent and satellite increases as function of repeated activation, practice determines when self-sustained activation ends and self-inhibition begins, and how long recovery lasts (unpracticed nodes require over 100 ms for recovery; see MacKay, 1987b, pp. 146-147).

In summary, dynamic properties of nodes such as activation, self-inhibition, priming, and linkage strength, taken individually as in the above discussion, are extremely simple, but taken together, these dynamic properties interact in complex ways that depend on the current state of the node and on its history of activity over the course of a lifetime. Priming is necessary for activation and is directly related to the probability of error (see MacKay, 1982). Activating a node increases the linkage strength of its connections and causes its connected nodes to become primed. Linkage strength in turn influences how much and how rapidly priming can be transmitted across a connection.

Activation of Content Nodes

The nodes I have been discussing so far are known as *content nodes*, because they represent the form or content of an action or perception, whether conscious or unconscious. I turn now to *sequence nodes*, the mechanisms for activating content nodes. Sequence nodes segregate content nodes into domains, activate the most primed content node in a domain, and determine the serial order in which content nodes become activated. As will be seen later, sequence nodes also call up the mechanism for prolonging activation and bringing the contents of perception and action into awareness.

Sequential Domains

Sequence nodes connect with a sequential domain, a set of content nodes representing units of behavior that all have the same sequential properties or privileges of occurrence in sequences involving other domains (see MacKay, 1987b, pp. 52-55). I use capital letters to denote sequence nodes and round brackets to denote a domain of content nodes. For example, the sequence node, COLOR ADJECTIVE[2] activates the domain (color adjective), the set of nodes representing color adjectives and sharing identical sequential properties or privileges of occurrence in English noun phrases.

Multiplication of Priming and the Most-Primed-Wins Principle

The Most-primed-Wins Principle is the basis for all node activation (see MacKay, 1987b, pp. 49-55) and follows directly from the way that sequence and content nodes connect with one another. Once a sequence node becomes activated, it repeatedly multiplies the priming of every node connect with it by some large factor within a relatively brief period of time. This multiplicative process has no effect on an unprimed node, but soon serves to activate (i.e., bring to threshold) the content

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[2] MacKay (1990) notes that the rule (color adjective + noun) may be derived or "inherited" from the more general rule (adjective + noun) whereby all adjectives precede nouns in English.

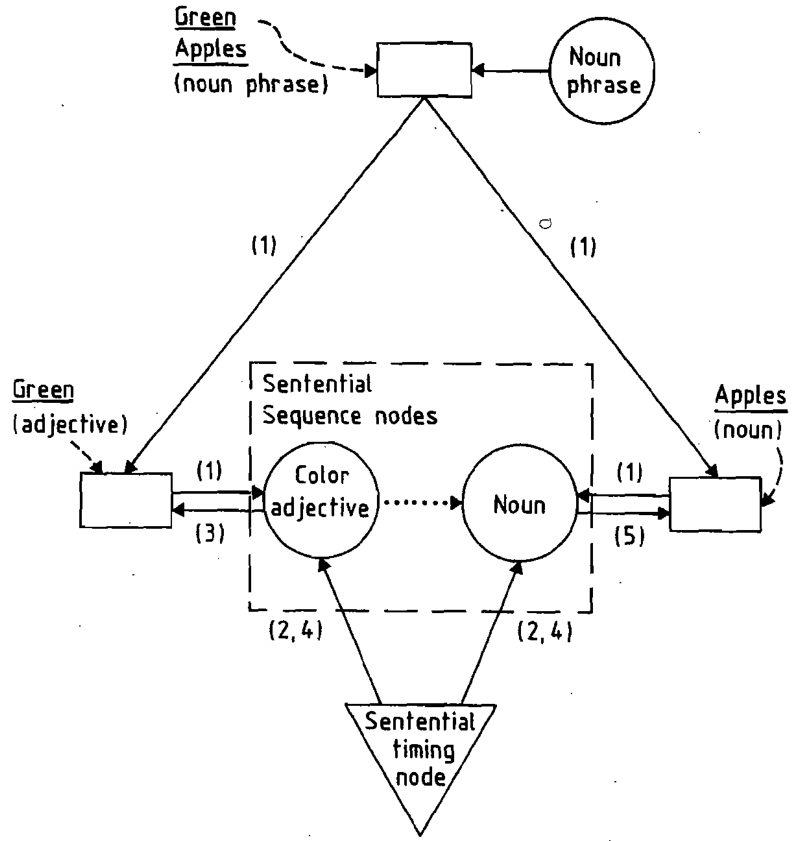

Fig. 3. The order (in *brackets*) of top-down processes underlying activation of content nodes (in *rectangles*), sequence nodes (in *circles*), and the sentential timing node (*triangle*) for producing the noun phrase *green apples*

node with the greatest degree of priming in its domain. For example, COLOR ADJECTIVE is connected to and, when activated, multiplies the priming of the dozens of content nodes in the domain (color adjective). Naturally, the node with more initial priming than all other nodes in its domain will reach threshold first, and this "most-primed" node will become activated.

During production, content nodes generally achieve their most-primed status via priming "from above." In producing the adjective *green*, for example, a superordinate node such as *green apples*(noun phrase) becomes activated, and strongly primes its connected nodes, including *green*(color adjective) (see Fig. 3). Being most primed when its activation mechanism is applied, the multiplied priming of this primed-from-above node reaches threshold sooner than the remaining "extraneous" nodes in its domain (i.e., nodes representing other color adjectives) and becomes activated.

During perception, content nodes achieve most-primed status mainly "from below." For example, visual inputs such as the color green or the printed word *green* will prime *green*(color adjective) from below. *Green*(color adjective) then passes second-order priming to its connected sequence node (see Fig. 3), enabling COLOR ADJECTIVE to become activated, and in turn to activate the most primed content node in its domain, *green*(color adjective) itself.

Quenching
Once a content node becomes activated, it quenches or inhibits, rather than further primes, its corresponding sequence node (see MacKay, 1987b, pp. 50-55), thereby ensuring that one and only one content node in a domain becomes activated at any one time. Quenching, together with multiplication of priming, therefore provides the functional basis for the most-primed-wins principle.

Activation of Sequence Nodes

Timing nodes activate sequence nodes and play a role in attention (discussed on pp. 290-293). They also control the rate of perception and action by determining how rapidly the sequence nodes become activated. Timing nodes connect with and activate sequence nodes in the same way that sequence nodes connect with and activate content nodes. However, timing nodes become activated according to an endogenous rhythm, and timing nodes for different systems of sequence nodes (e.g., the phonological system, the sentential system; see Fig. 1) have different endogenous rhythms. After each activation, timing nodes multiply the priming of sequence nodes connected to them, activating the most primed one on the basis of the most-primed-wins principle. This "most-primed sequence node" is, of course, usually the one that has just received second-order priming from a connected content node, e.g., *green*(color adjective) in the above example.

The Principle of Higher-Level Activation

Timing nodes for different systems, e.g., the phonological system and the speech muscle movement system, can be engaged or activated independently, and this provides the basis for selective attention (see pp. 290-292), for changing output mode (between, for example, *overt speech* where timing, sequence, and content nodes in all three systems become activated, versus *internal speech* where nodes in sentential and phonological systems activated but not those in muscle movement systems), and for a general perceptual principle called "higher-level activation" that plays a role in determining what units normally enter awareness. Under this principle, not all nodes in bottom-up hierarchies become activated during perception, the way they do during production in top-down hierarchies such as the one in Fig. 1: only nodes in higher level systems normally become activated and give rise to everyday perception. In particular, nodes in the sentential system normally become activated when perceiving conversational speech, whereas nodes in the phonological system do not (see MacKay, 1987b, pp. 74-84 for empirical, logical, and theoretical arguments for this principle).

Extension 1 of the Node Structure Theory: Awareness

Up to now I have been laying down a foundation on which to build a theory of awareness. Priming and activation are *necessary* for awareness, but not *sufficient*: awareness requires an additional mechanism. This section argues that the awareness mechanism is intimately related to novelty in perception and action, including the detection of self-produced errors, and I spell out an awareness mechanism for the node structure theory that has this property. I then argue that this awareness mechanism is necessary and sufficient for "commitment learning," the process whereby connections become functional in the node structure theory.

Novelty and Awareness in Perception and Action

The close relationship between consciousness and novelty has frequently been noted (e.g., Sokolov, 1963; Gregory, 1981). Consciousness seems necessary and sufficient for learning novel information: we normally become conscious of what is new, and what is old or frequently repeated drops out of awareness, as in habituation. When I say that I am aware of the familiar book before me on my desk, I am aware of the book in a novel context (e.g., a novel temporal context, or a novel spatial context relative to other objects on the desk). What is novel is not the book per se, but how its features conjoin in the present situation, and such novel feature conjunctions are a necessary condition for consciousness under the node structure theory. Similarly, when we become aware of a familiar word, it is not the meaning of the word per se that we become aware of, but word meaning in combination with its novel context of use.

The correlation between novelty and awareness has also been demonstrated experimentally. For example, MacKay (1973a) showed that novelty and awareness are correlated in language comprehension, so that awareness is necessary for forming novel (deep structure) integrations of the meanings of words in sentences. Specifically, MacKay showed that sentences undergo deep structure analyses during conscious but not during unconscious processing (via the unattended channel in a dichotic listening experiment). The highly familiar meanings and syntactic categories of words in the unattended channel received unconscious processing (priming), but failed to enter awareness. However, comprehending what was new - the particular conjunction or relation between words in the context in which they were spoken - required conscious processing. Treisman and Gelade (1980) demonstrated a similar correlation between consciousness and the integration of separately processed visual features (e.g., color and form) of objects. Without sufficient time for awareness, these separate features failed to become conjoined to enable object recognition.

Binding Nodes and Prolonged Activation: The Awareness Mechanism

The necessary and sufficient condition for conscious awareness in the node structure theory is prolonged activation: we become conscious of novel conjunctions of concepts during the time when the nodes representing those concepts are undergoing prolonged activation. This section examines the triggering mechanisms for prolonged activation, while subsequent sections examine the more complex process whereby binding nodes are called up and results in the formation of new connections.

How Binding Nodes Prolong Activation

Binding nodes prolong activation by inhibiting the self-inhibition mechanism of two or more sequential domains of content nodes. That is, binding nodes connect with two or more domains of content nodes, are inhibitory in nature, and connect not with the parent node but with its self-inhibitory satellite. An activated binding node therefore shuts down the self-inhibitory mechanisms of all content nodes to which it is connected. This causes currently activated nodes to remain activated for a prolonged period of time because they can no longer self-inhibit. Thus, although binding nodes connect with many content nodes, their effect is specific: they only alter the behavior of the small subset of connected nodes that happen to be activated at the time.

Comparison with Other Theories of Awareness

The node structure theory of awareness resembles other accounts in some respects but not others. Unlike other theories, the node structure theory relates consciousness to a strictly temporal factor: prolonged activation. Also, the same nodes represent a content either consciously or unconsciously, but not both simultaneously in the node structure theory, unlike the theories of, say, Baars (1983, 1988) and Thatcher and John (1977) where one system represents conscious contents and another (separate) system represents unconscious contents, with the same information or experience represented consciously in one place and unconsciously in the other. However, a conscious content is more than just a different state of a single, already-established representation in the node structure theory. Two different types of representation (committed versus uncommitted nodes) and a state change (increased linkage strength; see pp. 274-275) underly consciousness.

Pertinent Novelty and the Activation of Binding Nodes

I will use the term "pertinent novelty" to refer to the conditions that trigger binding nodes, causing prolonged activation and awareness. Pertinent novelty occurs whenever two or more committed nodes that have rarely or never been activated in simultaneous combination before become activated simultaneously or in temporal overlap and call up an existing higher-level sequence node via an uncommitted node. Understanding the distinction between committed versus uncommitted nodes is therefore necessary for understanding how binding nodes become activated.

Committed Versus Uncommitted Nodes

Up to now, all nodes discussed in the node structure theory have been committed nodes, defined in terms of the strength of their connections: connections *to* committed nodes are strong enough for the committed node to receive sufficient priming to enable activation when its activation mechanism (sequence node) is applied. Similarly, connections *from* committed nodes are strong enough for connected nodes to be able to become activated when their activating mechanism is applied. That is, in order to become activated, a node must achieve a minimal level of priming in addition to most-primed status in its domain. Without surpassing this minimal level, or commitment threshold, priming multiplied by an activating mechanism cannot reach the level required for activation.

Uncommitted nodes are likewise defined in terms of the strength of their connections: connections *to* uncommitted nodes are so weak that they cannot receive enough priming to reach commitment threshold or to achieve most-primed status in their domain and become activated when their activating mechanism is applied. Connections *from* uncommitted nodes are likewise so weak that they transmit too little priming for connected nodes to become activated when their activation mechanism is applied.

Most mental nodes begin with uncommitted status: they have weak or uncommitted connections. However, these uncommitted connections are prewired into hierarchically organized domains, such that nodes in two or more sequentially organized domains connect convergently with nodes in a single superordinate domain. That is, between any pair of uncommitted nodes in sequentially organized subordinate domains, there exists at least one uncommitted node in a superordinate domain that receives convergent connections from both of them. For example, every pair of uncommitted nodes in domains that come to represent (initial consonant group) and (vowel group) converges on at least one uncommitted node in the domain that comes to represent (syllable). This is not to say that the *particular content of a domain* comes prewired in the newborn. Only the organizational structure for sequential domains comes prewired: what particular content a prewired domain comes to represent is a matter of experiential factors such as order of acquisition. Nor is this to say that only a single pair of subordinate nodes contributes conjoint connections to any given uncommitted node, although this may in fact be true of nodes in the phonological system. However, uncommitted nodes in the sentential system will exhibit *multiple convergence*, or receive conjoint connections from many pairs of subordinate nodes.

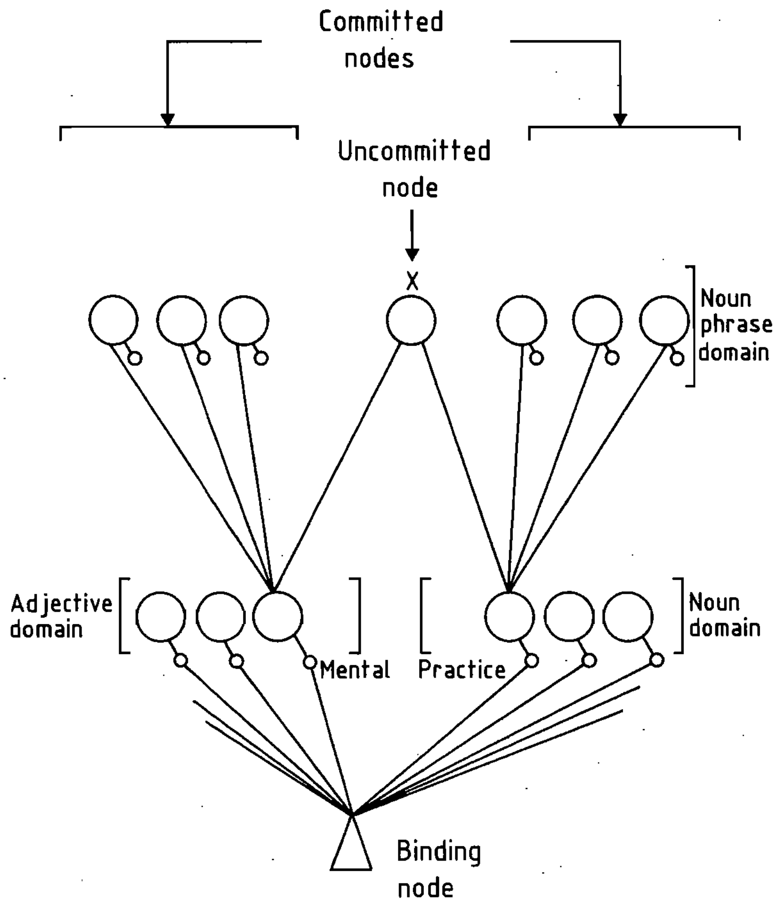

Fig. 4. The NOUN PHRASE binding node (*triangle*) prolongs activation of currently activated nodes, *mental*(adjective) and *practice*(noun), by inhibiting the inhibitory satellites (*small circles*) of committed parent nodes (*larger circles*) in the (adjective) and (noun) domains. NOUN PHRASE also commits uncommitted node X to represent the content *mental practice*(noun phrase)

How Pertinent Novelty Triggers Binding Nodes

The mechanism whereby pertinent novelty triggers binding nodes is as follows: sequence nodes are connected to a binding node with a very high threshold that cannot be reached when the sequence node is simply activated and then quenched. Now, when two or more committed nodes become activated simultaneously or in temporal overlap, they contribute conjoint first-order priming to an uncommitted node, and second-order priming to its sequence node via many nodes (see Fig. 4). The sequence node will therefore become activated but fail to activate the uncommitted node or any other nodes in its domain. The sequence node therefore "fails to quench" and remains activated for a prolonged period, and this prolonged activation triggers the binding node via temporal summation.

Pertinent Novelty, Orienting Reactions, and Errors

Convergent priming arriving at an uncommitted node can be said to signal pertinent novelty in the node structure theory; so does the "failure to quench" of its sequence node. For example, the expression "inhibitory satellite" constitutes an instance of pertinent novelty if the hearer "knows" that an adjective followed by a noun constitutes a noun phrase, but has never experienced this particular combination of adjective and noun before: no node has been committed to the content *inhibitory satellite*(noun phrase). Thus, when the sequence node NOUN PHRASE is activated, none of the nodes in its domain has accumulated enough priming to become activated, so that NOUN PHRASE fails to quench and triggers its binding node, causing prolonged activation, and awareness.

Orienting Reactions: Side-Effects of Pertinent Novelty

Besides activating binding nodes, pertinent novelty automatically triggers orienting reactions that include emotional components, e.g., surprise; autonomic components, e.g., increased skin conductance, cardiac deceleration, and pupil dilation; and behavioral components, e.g., inhibition of ongoing activity (Neumann, 1987). Thus, unlike other theories, such as Sokolov (1963) and Baars (1988), the node structure theory generates orienting responses without complicated mismatch mechanisms for comparing new models with prior models of the internal or external world.

Pertinent Novelty and Error Detection

Errors result in the activation or production of a sequence of units that is novel at some level. For example, *dump seat* misproduced as *sump deat* involves novel lexical units because *sump* and *deat* are nonwords in English. Similarly, *crawl space* misproduced as *crawl srace* involves a novel phonological unit because syllable-initial *sr* does not occur in English. *Fly the plane and buy the boat* misproduced as *Fly the boat and buy the plane* involves a novel propositional unit because boats do not fly. Similarly, *tool carts* misproduced as *cool tarts* in the intended sentence *They were moving tool carts down the assembly line* involves a novel propositional unit if the speaker lacks a committed node for *They were moving cool tarts down the assembly line*(proposition) (examples from Motley, Baars, & Camden, 1983).

Speech errors therefore introduce pertinent novelty that can trigger orienting reactions and signal occurrence of an error. However, different errors differ in the number of connections between the units produced in error and the uncommitted node that they prime, and this "distance" plays a role in error detection. Compare the effects of this distance for two phonological transposition errors (above): *crawl srace* instead of *crawl space*, and *cool tarts* instead of *tool carts* in the intended sentence *They were moving tool carts down the assembly line*. In *crawl srace*, no committed node represents *sr* (initial consonant group) for speakers of English, so that when *s*(initial stop) and *r*(initial liquid) are activated in error, first-order bottom-up convergent priming is transmitted immediately (distance 0) to an uncommitted phonological node, thereby triggering binding nodes, orienting reactions (causing output to terminate: see above), node commitment, and *awareness* (prolonged activation) that enables error detection. Indeed, this rapid detection sequence may explain why phonologically novel errors are so rare in overt speech (see Fromkin, 1971): these errors can be detected so rapidly as to prevent their occurrence before they appear in the surface output (see MacKay, 1990; Levelt, 1984).

However, error detection will be both less efficient and less likely when many intervening connections separate the uncommitted node from the phonological units produced in error. In the *cool tarts* error, for example, nodes higher in the hierarchy already exist for representing the segments *c*(initial consonant group) and *t*(initial consonant group), the syllables *cool*(stressed syllable) and *tarts* (stressed syllable), and the words *cool*(adjective) and *tarts*(noun). Even *cool tarts* (noun phrase) is likely to exist as an already committed node, precluding the possibility of orienting reactions and error detection at that level. However, the proposition node *They were moving cool tarts down the assembly line*(proposition) almost certainly does not exist as an already committed node, so that activating *cool tarts* (noun phrase) in the context *move down the assembly line* could potentially trigger orienting reactions and awareness of the error. However, *cool tarts*(noun phrase) is unlikely to achieve greatest priming in its domain and become activated while producing the remainder of this sentence because many connections separate cool tarts(noun phrase) from its source of first-order priming at the phonological level. In consequence, such an error is likely to pass undetected, and the node structure theory predicts that probability of error detection will vary with the proximity of units produced in error to the uncommitted node that they prime. Indeed, this proximity factor may contribute to the fact that speakers fail to detect or correct about 40% of the word substitution errors that occur. (See MacKay, 1990, for further discussion of error detection.)

Internally Generated Pertinent Novelty

As the above discussion suggests, the novel conjunctions providing the basis for awareness need not originate in the external world under the node structure theory. People can actively become aware of familiar objects and concepts by generating pertinent novelty internally: activating a novel combination of nodes in sequentially related domains will give rise to awareness regardless of whether the novel combination arises from internal or external sources. Indeed, novel conjunctions from internal sources not only provide conscious contents (images) without environmental help; they make possible the mental simulation of past and possible (future) events that is essential for planning adaptive actions.

Connection Formation: The Commitment Process

As discussed above, the brain comes equipped with an excess of uncommitted nodes with extremely weak but prewired or potential connections. The question is how one or more of the hundreds of uncommitted connections to an uncommitted node become committed or "functional", i.e., capable of transmitting enough priming to enable activation. This section argues that the awareness mechanism discussed above is necessary and sufficient for commitment learning. Uncommitted connections automatically become committed when inputs never previously experienced fall into familiar classes, and when outputs never previously produced are created, and give rise to awareness. Because most everyday sentences are new or never previously experienced, new connections to at least one new (proposition) node must become committed when comprehending or creating novel sentences, according to the theory. Conversely, if I remember novel information such as the place on a page where I read a particular fact, I must have been conscious of this page position when I initially learned the fact, according to the theory.

Binding Nodes and Prolonged Activation as Commitment Mechanisms

The uncommitted node receiving convergent connections from two or more committed nodes undergoing prolonged activation (see p. 282 and Fig. 4) achieves commitment levels of priming via temporal summation and becomes activated via its (unquenched) sequence node as the most-primed node in its domain. Activating the uncommitted node in turn causes a slight but relatively ling-term increase in linkage strength across its connections, thereby improving the asymptotic level and rate of priming via those connections. With further activations, linkage strength increases further, until bottom-up priming suffices to enable activation without the boost in bottom-up priming that results from prolonged activation and awareness. The uncommitted node has now been transformed into a committed node that consistently codes a particular cognitive content. Future activation proceeds automatically via the most-primed-wins principle and is followed by self-inhibition, so that consciousness can no longer occur: self-inhibition automatically shuts off activation after a set period, precluding the prolonged activation necessary for awareness.

Commitment of Bottom-up Connections

To illustrate how a binding node transforms an uncommitted node into a committed one in the theory, consider the child who knows the concepts *mental and practice* but has just encountered the expression *mental practice* for the first time. That is, there exist two parent nodes, represented *mental*(adjective) and *practice*(noun), each with an inhibitory satellite shown Fig. 4. The parent node labeled *mental* (adjective) is connected to several nodes in the (noun phrase) domain, including committed nodes such as, say, *mental arithmetic*(noun phrase), and uncommitted nodes such as the one labeled X in Fig. 4. The child also has a committed node *practice*(noun) connected to this same uncommitted node X as well as to perhaps several hundred other nodes, including, say, the committed node *piano practice* (noun phrase). Thus, despite its convergent (spatially and temporally summating) input, uncommitted node X may not receive greatest priming in its domain during the normal period that *mental*(adjective) and *practice*(noun) remain activated, and in any case, the convergent priming is too weak to enable activation of X when its triggering mechanism (NOUN PHRASE) becomes activated. NOUN PHRASE therefore fails to quench.

We now require a notational convention: bold capitals will denote binding nodes and square brackets will denote the corresponding domain of inhibitory satellites of the binding node. Thus, the domain for the binding node **NOUN PHRASE** (see Fig. 4) is [noun phrase], and includes the inhibitory satellites of content nodes representing immediate constituents of noun phrases, i.e., (adjective) and (noun), among others. When NOUN PHRASE in Fig. 4 fails to quench, **NOUN PHRASE** becomes activated, thereby inhibiting the self-inhibitory mechanisms of nodes in [noun phrase]. As a consequence, nodes in the domain [noun phrase] that are currently activated, specifically *mental*(adjective) and *practice* (noun), fail to self-inhibit, and so engage in prolonged activation. This provides uncommitted node X with the required boost in priming (via temporal and spatial summation), so that NOUN PHRASE can now activate X. Activation of X increases the linkage strength of its bottom-up connections, and with repeated activation enables X to code the content *mental practice*(noun phrase) without engaging **NOUN PHRASE** for introducing prolonged first-order bottom-up priming.

More generally, the bottom-up binding process goes as follows: two or more lower level committed nodes, A, B,..., become activated on the basis of priming from internal or external (environmental) sources and send temporally overlapping first-order priming to an uncommitted node, X. The problem is that, without outside help, the temporal and spatial summation of priming from A + B +... cannot reach commitment level, because A + B +... normally become self-inhibited soon after activation. The outside help comes indirectly from X's sequence node, which fails to quench, and thereby activates its binding node. The binding node inhibits the self-inhibitory satellites for A + B +..., thereby causing prolonged activation of A + B +.... This prolonged activation extends the duration of temporal summation at uncommitted node X, enabling X to reach commitment threshold and become activated.

Commitment of Top-down Connections

Once bottom-up connections to an uncommitted node become functional, top-down connections can become committed almost immediately, without further engagement or reactivation of the binding nodes. Specifically, once an uncommitted node becomes activated, it transmits first-order priming to all of its connected nodes, including the lower-level nodes that are still undergoing prolonged activation. Because a connection transmitting first-order priming to an activated node constitutes the basic condition for greatly increasing linkage strength, top-down connections become strengthened soon after their newly committed constituent node becomes activated. For example, during the time that X in Fig. 4 remains activated, the appropriate top-down connections can become strengthened almost immediately, because X now provides (two) activated nodes with first-order priming, the basic condition for a major increase in linkage strength. Of course, X also has uncommitted top-down connections to many other nodes, but only *mental* (adjective) and *practice*(noun) will meet this condition for increasing linkage strength to commitment levels. As a result, X now represents the specific content *mental practice*(noun phrase) for both input and output, albeit still relatively weakly.

Consciousness and Connection Formation In Vacuo

Because events and internal states are continuously changing and introducing pertinent novelties for humans in the waking state, conscious experience normally seems continuous (like a stream; James, 1890); nodes in one and often many input and output systems are undergoing prolonged activation, and we are continually aware of some novel aspect of our internal or external environment. However, without a changing environment or changing internal goals, the process of novel connection formation and consciousness seems to run off internally *in vacuo*: humans experience visual, auditory, and tactile hallucinations following prolonged periods of inactivity and sensory deprivation (Hebb, 1963). These hallucinations reflect internally generated pertinent novelty, or simultaneous activations of novel combinations of nodes, a necessary condition for connection formation and awareness. Dreams may represent another case where connection formation runs off internally in "unexpected and bizarre combinations" (Mandler, 1985, p. 80) due in part to reduced motoric activity and reduced bottom-up input from the environment.

Comparison with Retrieval Theories of Learning and Awareness

The node structure theory differs from retrieval theories of learning and awareness (see Baars, 1988). In retrieval theories, memory items enter consciousness (short-term memory) whenever they become activated, but, without rehearsal, no long-term connections whatsoever are established between the consciously represented items. The node structure theory goes beyond retrieval theories by providing a mechanism for explaining the effects of rehearsal (MacKay, 1981) and by providing a mechanism whereby new words, new phrases, and new experiences in general can be learned without rehearsal, simply by entering consciousness.

Decommitment, the Grandmother Cell Problem, and Amnesia

One or even several activations of an uncommitted node introduce only minor increases in linkage strength that can undergo atrophy or complete decay over a period of, say, a few days. As a result, unless weakly committed nodes undergo repeated activation, their connections can become decommitted or revert to uncommitted status. This means that a binding node may have to become engaged several times before the uncommitted node representing a particular instance of pertinent novelty becomes permanently committed and automatically activated. However, once a node's connections have become strongly committed, its remaining preexisting connections undergo atrophy so that it can no longer code any other content.

The Grandmother Cell Problem

The mechanisms of decommitment and multiple convergence provide an interesting solution to the "grandmother cell problem," the claim that theories incorporating "local" rather than "distributed" representations for relatively unique events such as sentences require an inordinate number of units. The node structure theory does not permanently code unique events, and the same uncommitted node can code many different contents, limited only by its degree of multiple convergence, and by the nonrecurrence of its contents: newly formed connections that remain unused undergo atrophy and become decommitted. Both of these preconditions are assumed to hold for nodes in sentential domains such as (active declarative proposition) where particular contents are repeated so rarely that permanent commitment is both unlikely and unnecessary. Only when the same sentence is perceived or produced repeatedly does its proposition node become permanently committed and incapable of coding alternate contents. Both of these preconditions hold in a similar way for visual cognition: permanent commitment is possible for a frequently experienced visual event such as one's grandmother, but not for an infrequently experienced visual event such as "my grandmother seen from behind walking past a desk in the parlor": if node commitment occurs at all for a nonrepeated event such as this, decommitment soon follows.

One interesting implication of the node structure solution to the grandmother cell problem is that uncommitted nodes require greater multiple convergence in higher level systems than in lower level systems. Uncommitted nodes in higher-level systems, e.g., the sentential system, where decommitment is common should exhibit an abundance of multiple conjoint connections, so that the same node can be reused repeatedly for representing novel contents. However, nodes with multiple conjoint connections should be less common in lower level systems, e.g., the phonological system, where decommitment is rare.

The node structure theory calls for a reanalysis of other assumptions implicit in formulations of the grandmother cell problem. One is that units exhibit only one type of processing (activation) and another is that units higher in a hierarchy exhibit the same behavior as units lower in a hierarchy (see D.M. MacKay, 1985). The fact that experimental evidence has not in general supported these assumptions (see, for example, D.M. MacKay, 1985) is consistent with the node structure distinction between types of processing (priming versus activation) with lower-level nodes behaving differently from higher-level nodes: under the principle of higher level activation, nodes higher in a hierarchy invariably become activated during perception, whereas nodes lower in a hierarchy can pass on priming without necessarily becoming activated. The node structure theory also calls for reanalysis of a third assumption implicit in formulations of the grandmother cell problem, namely that the filtering operations performed by feature detectors are directly responsible for "recognizing" the geometrical form of objects (see D.M. MacKay, 1985): conscious recognition requires more than simple classification in the node structure theory.

Binding Nodes and Amnesia

Binding nodes for speech perception-production are represented in the brain in structures such as the hippocampus and become engaged whenever an internally or externally generated verbal experience falls into a known category or domain, but is otherwise novel, so that a linguistic sequence node becomes activated but fails to activate any nodes in its domain. When this happens, the sequence node fails to quench and causes its connected high-threshold binding node to become activated.

The assumption that bilateral hippocampal and mediotemporal lesions destroy many of the binding nodes required for forming new long-term traces in higher-level language systems fits well with the pattern of sparing and deficit in amnesic patients (Squire, 1987; Shachter, 1985; Milner, 1968). Without input from the binding nodes for committing uncommitted connections, long-term learning of language inputs stops on the day of the operation. However, connections formed prior to the operation remain functional in hippocampal patients (see Squire, 1987, Milner, 1968) because bottom-up inputs still prime and enable activation of already committed nodes without help from the lesioned binding nodes: bilateral hippocampal damage cannot affect already established connections that are automatically primed and activated. As a result, densely amnesic patients show normal priming effects via already established connections, e.g., in a word completion task, even though they cannot form the new connections required to enable conscious verbal recall of having performed the task before (see, for example, Shachter, 1985).

However, higher-level language systems constitute a small sample of many systems that contain binding nodes for triggering awareness and connection formation. Other perception and action modules have their own (as yet undiscovered) systems of binding nodes, including those for classical conditioning of, say, the eyeblink reflex, and these other binding nodes are assumed to be intact in "language" amnesics. As a result, language amnesics are unaware of higher level language inputs,but not entirely unconscious or entirely incapable of learning: they can still learn nonlanguage behaviors such as the solution to a tactile maze, for example (see Corkin et al., 1985), even though they cannot verbally recall having seen or learned the maze before: nonverbal binding nodes suffice for learning a tactile maze, but verbal binding nodes are required for answering a verbal question about a tactile maze.

The fact that binding nodes are inhibitory in nature and only become engaged for novel inputs is consistent with recent observations on electrophysiological responses from the hippocampus: Smith (1986) and Smith, Stapleton, and Halgren (1986) recorded event-related potentials intracranially in humans performing recognition memory tasks involving repeated trials, and for novel inputs they observed temporally consistent long-latency (460 ms) potentials emanating from the hippocampus. Moreover, these hippocampal potentials appeared to be *inhibitory* in nature and disappeared after several trials, as if they reflected the inhibitory output from binding nodes for forming novel connections in the language system.

Finally, the fact that binding nodes become engaged automatically in response to pertinent novelty overcomes a problem with Wickelgren's (1979) proposal that the binding mechanism is excitatory in nature and selectively activates only uncommitted nodes by somehow forming a return inhibitory connection to the hippocampus once the uncommitted node has become committed. Wickelgren's otherwise excellent proposal requires connection formation for forming connections, a *reductio ad absurdum.*

Extension 2 of the Node Structure Theory: Attention

When we want someone to learn something new, we "call it to their attention," and it is often assumed that attention is necessary for learning and awareness (see Baars, 1988). Under the node structure theory, this common sense notion is only partially correct: commitment learning and awareness are coreferential in the theory, and although attention can help to activate particular contents, and activation is a precondition for awareness, attention is only necessary for learning and awareness under special circumstances. Moreover, the mechanisms underlying attention are essential for other purposes in the node structure theory, unlike theories such as Crick's (1984) where attention requires a special "searchlight" mechanism and a special type of (temporary) connection formation. The active direction of attention nevertheless remains a borderline phenomenon within the node structure theory: a complete theory of how attention is directed must provide an account of motivation, something the node structure theory does not do. What happens *after* a person chooses to attend to one source of input rather than another lies within the scope of the theory, but not the basis for choice per se. Within this limit, however, the node structure theory readily captures relations between awareness and attention, as I outline briefly below.

Selective Attention and Awareness

What are the theoretical mechanisms that enable people to selectively respond to one source of input rather than another? Two mechanisms already required for other purposes in the theory accomplish selective attention. One is the most-primed-wins principle that automatically activates target nodes whenever they receive more priming than distractor nodes in the same domain. For example, the most-primed-wins principle resolves ambiguities at various representational levels during perception by ensuring that only nodes representing the dominant (most frequent) or contextually most supported interpretation become activated and provide the basis for awareness (MacKay, 1987b, pp. 134-136). In short, the most-primed-wins principle automatically enables us to selectively ignore or fail to respond to the huge number of weaker inputs that are arriving simultaneously from the environment. Of course, the most-primed-wins principle also selectively activates target nodes whenever target and distractor inputs do not share domains of mental nodes, as when speech is presented to the left ear and a violin concerto to the right.

Here different-domain inputs are ignored because the timing and sequence nodes for activating nodes in these nonspeech domains are not applied.

The mechanism for engaging the activating mechanisms (timing nodes and sequence nodes) for systems of content nodes representing one source of input rather than another therefore provides another means of achieving selective attention (see MacKay, 1982). Consider shadowing, for example, a standard empirical paradigm for demonstrating selective attention: when different paragraphs are presented simultaneously to each ear, subjects can selectively shadow or reproduce with minimal lag one paragraph with little interference from the other paragraph. Under the node structure theory, shadowing tasks require activation of "target nodes" (that have been primed via one channel, say, the right ear) but not "distractor nodes" (that have been primed via other channels). This task becomes problematic when target and distractor inputs are similar and simultaneously prime nodes in the same domain: whatever node in this shared domain happens to be most primed will become activated under the most-primed-wins principle, regardless of its channel of origin, and when distractor rather than target nodes become activated, a "cross-talk" intrusion from the other channel will occur.

To prevent these cross-talk errors, activating mechanisms (timing nodes and sequence nodes) must become engaged at a lower than normal level for systems of content nodes that distinctively represent inputs from the target source rather than from the distractor source. The resultant node activations deliver a boost in priming to low-level nodes representing target inputs rather than distractor inputs, and this (first-order) boost in priming gets transmitted to target nodes in higher-level (shared) domains, enabling them to become activated under the most-primed-wins principle instead of distractor nodes (that lack this boost in priming). For example, when subjects are instructed to shadow speech inputs arriving at the right rather than the left ear, both sources of input prime nodes within shared domains in the phonological system (and above), but there exist lower-level domains of sensory analysis nodes (closer to the basilar membrane) that are unique to the right ear. Engaging the activating mechanisms for these unique lower level domains introduces first-order convergent priming that enables (connected) nodes for right ear (target) inputs to become most primed in (shared) phonological domains and become activated so as to determine the shadowing response[3].

One interesting implication of this view of selective attention is that comprehension will require more time under conditions requiring selective attention than under conditions not requiring selective attention. The reasoning goes as follows. Because lower-level nodes do not normally become activated during everyday comprehension (the principle of higher-level activation), but do become activated in selective attention tasks, more nodes than normal must become activated in selective attention tasks. Because activation proceeds sequentially and requires more time than priming (see MacKay, 1987b, pp. 77-78), comprehension will require more time when a task requires selective attention. For example, recognizing a

[3] This is not to say that attentional selectivity is *in general* based on distance from the sensory receptors: For example spatial selectivity is possible when both ears receive competing messages, and intensity or interaural time differences can be used to code spatial location.

semantic target (names of animals, say) will take more time under conditions requiring selective attention than under conditions not requiring selective attention. Similarly, as the rate of presenting a paragraph is speeded up via computer-compression techniques, comprehension should break down at slower rates when selective attention is required than when selective attention is not required.

Flexibility of Higher-Level Activation

As the above discussion suggests, higher-level activation is a relative rather than an absolute principle: it is not just possible but desirable to engage the timing nodes for activating lower-level systems of nodes whenever an input is especially degraded, or unfamiliar, or requires selective attention. Activating these lower-level systems incurs costs such as reduced rates of processing, but paying these costs is necessary in these situations to provide sufficient bottom-up priming to enable appropriate higher-level nodes to become activated.

Divided Attention and Awareness

"Dividing" attention between different output or perceptual-motor systems, as when we carry on a conversation and drive a car at the same time, requires the same mechanisms as selective attention in the theory (given the decision to carry on both activities simultaneously): the most-primed-wins principle, and the mechanisms for (simultaneously) engaging the activating mechanisms (timing nodes and sequence nodes) for the two or more systems of content nodes representing the concurrent activities. Divided attention is achieved within the theory by simultaneously activating nodes in different domains, on the input side (sensory analysis nodes), on the output side (muscle movement nodes), or both (mental nodes), and the theory predicts interference whenever the concurrent activities share nodes in the same domain.

However, nodes in shared domains represent only part of the reason why people tend to make errors when attempting to do two similar tasks simultaneously. The degree and nature of interference also depends on the type of shared node (content versus sequence versus timing nodes), on their temporal pattern of activity, and on the nature of their interconnections. Besides providing some interesting predictions, these mechanisms in the theory explain a wide range of already observed interference and noninterference effects. For example, the most-primed-wins principle allows error-free execution of two or more concurrent activities if the nodes that must be simultaneously activated inhabit different domains. This means that complex activities such as speaking, typing, or playing the piano can be executed concurrently and automatically without mutual interference, but only if prior learning and practice have established nodes for these activities in separate domains at every level of the system.

In conclusion, attention and consciousness are closely interrelated and interact with one another in the node structure theory: with conflicting sources of input, attention can play a role in determining what source of perceptual inputs become activated and enters awareness. However, awareness and attention reflect different processes under the theory. Awareness is a direct and ongoing consequence of commitment learning, whereas the learning that is required for divided and selective attention has already taken place. Moreover, awareness can occur automatically, without the aid of the motivational mechanism that is required to direct attention toward different types of perceptual or output activities.

Comparison with Other Theories of Attention

The mechanisms for attention in the node structure theory, e.g., the most-primed-wins principle, can be seen to exhibit general characteristics of two major, currently competing approaches to attention: the capacity limitation approach (Kahneman, 1973) and the distributed control approach (see Allport, 1980). However, the node structure theory achieves these characteristics using very different mechanisms from either of these approaches: capacity is limited because only one content node in a domain can become activated at a time under the theory, and processing is distributed because content nodes in different domains and systems can and often do become activated simultaneously.

New Insights into the Three-Body Problem

I now return to the empirical questions that began this chapter, starting with the three-body problem, part 1; vicissitudes of awareness in perception and action. My goal is to summarize observed relations within the vast literature on action, perception, and awareness that now make theoretical sense, although I must leave for a future publication the details of how the node structure theory explains some of these phenomena.

Vicissitudes: Level of Awareness Rules in Perception and Action

Because the node structure theory provides a detailed representation of what is above what in language perception and production, the concepts of "level of processing" and "level of awareness" can be well defined in the theory. The node structure theory also makes sense of the "level of awareness rule," the fact that we normally become conscious of higher- rather than lower-level units in perception and action (see MacKay, 1973a). The level of awareness rule is attributable to the inverse relation between level and linkage strength (practice) in the node structure theory. Phonological nodes generally receive more prior practice than lexical and phrase nodes (see MacKay, 1982), which in turn receive more prior practice than the proposition nodes that must become committed *de novo* when perceiving or producing sentences that have never previously been encountered. As a result, connection formation and awareness are usually limited to higher-level concepts because what is new (unhabitual and unhabituated) triggers consciousness, and what is usually new in everyday sentences is not phonemes but phrases and propositions.

Exceptions to the Level of Awareness Rule

The node structure theory also makes sense of the many exceptions to the level of awareness rule. For example, although awareness normally begins at the lexical level for adults producing everyday speech (MacKay, 1987b, p. 79), adults occasionally learn new words that only approach automaticity at the phonological and lexical levels after considerable practice. Moreover, if concepts at higher (suprasentential) levels receive sufficient practice, they too achieve automaticity or unconscious processing. Even everyday thought patterns involving discourse level units can receive so much practice as to become triggered automatically and unconsciously (see Freud, 1914; MacKay & Konishi, 1980).

Errors in speech and action illustrate another important exception to the level of awareness rule (discussed above). Speakers normally become acutely aware of a speech error, even a subphonemic error such as the slurring of a speech sound (see MacKay, 1990). The nature of the slur, what sound was slurred and perhaps also the higher-level implications of the slur for the speaker enter awareness. Similarly, when listening to an unaccustomed foreign accent, we become aware of *both* the low-level articulatory novelties *and* the functionally useful (pragmatic) message being conveyed. Finally, aspects of the environment often enter awareness automatically when an error occurs, as when seasoned drivers become aware of their previously unconscious driving behavior after experiencing a near miss, or an unexpected traffic light (see Mandler, 1985).

These exceptions show again that the level where conscious processing begins is not completely fixed. We adults *normally* only become aware of higher-level aspects of an input, i.e., the sentential and discourse levels in the case of language, and objects and ego space in the case of vision (Marcel, 1983), and we *normally* remain unaware of the sensory and lower level conceptual events, e.g., phonemes, whose priming contributes to determining that awareness. However, consciousness can begin at a lower than normal level when an input is attended to, novel, unexpected, degraded, or unfamiliar: either attention or pertinent novelty (as in the case of speech errors) can engage the mechanisms necessary for consciousness and connection formation at lower than normal levels, enabling phonological or even sensory and muscle movement information to enter awareness.

Vicissitudes in the Adaptive Value of Awareness

Consciousness is closely connected with the organization of action under the node structure theory: the prolonged and simultaneous activation of two or more nodes that results in consciousness forms new nodes for joining formerly disparate action components together in the service of a higher plan. The prolonged activation associated with consciousness also facilitates the rapid preparation of adaptive responses by priming or preparing for retrieval stored information relevant to the current situation. When a concept enters awareness, all of the mental nodes (information and actions) associated with it become very strongly primed or prepared for activation: the conscious organism is in a continual state of readiness to use a wide range of past experiences for responding to what's new in an ongoing situation. However, the benefits of prolonged activation and awareness vary with the structure of the overall network. If a (hypothetical) organism can respond only on the basis of preformed stimulus-response connections, responses that are unconscious, fast, and unmodifiable are preferable to responses that are conscious and modifiable, but slow. Prolonged activation and awareness are neither necessary nor necessarily adaptive for all perceptual-motor systems.

Language as an Imperfect Index of Awareness

Language is generally accepted as the main index of awareness because verbal systems constitute our most sophisticated and frequently used means of representing and expressing our awareness in everyday life: the large number of domains of nodes required for language facilitate the formation of new (conscious) representations, and once formed, language representations can be used immediately, e.g., in communicating with other people. However, contrary to Vygotsky (1962), our ability to verbally comment (either overtly or internally) on our percepts, thoughts. memories, or behaviors is not a necessary precondition for consciousness. When we become aware of something, we can *usually* identify it by means of a verbal response, but consciousness is neither synonymous with verbal awareness nor a direct product of our ability to speak. For example, one often becomes aware of a novel experience, say, an unfamiliar smell, without being able to find words to describe it appropriately. Words can even fail us for describing everyday objects and events of which we are undeniably aware, as during the tip-of-the-tongue state (James, 1890). Finally, most psychologists would hesitate to deny awareness to the aphasic who is incapable of speech but can compose a symphony or paint a portrait (Luria, 1980). In short, there exist other, nonverbal awareness systems as in the node structure theory.

Interactions Between Conscious and Unconscious Processes in Perception and Action

The three-body problem, part 2, consists of two questions. I consider the first of these questions here: how do unconscious processes give rise to perception and action without awareness on the one hand, and errors in perception and action on the other?

Perception Without Awareness

The vast literature on perception without awareness (see Dixon, 1981) illustrates effects of unconscious processes (priming) on conscious ones in ways that make systematic sense under the node structure theory. I touch briefly on several of the more salient examples. One is Corteen and Wood's (1972) study on conditioned galvanic skin responses (GSRs) to shock-paired words presented to the unattended ear in a dichotic listening-shadowing task. Corteen and Wood first paired the target words with shock and then presented these words interspersed among other, neutral words on the unattended channel. As commonly occurs during dichotic listening, the subjects were unaware of these unattended target words and unable to signal their occurrence by making a manual response or by stopping shadowing. However, both the shock-paired words and their semantic relatives elicited GSRs whether presented to the shadowed or to the unshadowed ear. These findings clearly illustrate semantic processing without awareness of the input to the unattended channel, and have now been successfully replicated in at least five published experiments (see Neumann, 1984).

MacKay's (1973a) experiments on selective listening also illustrate semantic processing without awareness and are consistent with the findings of Corteen and Wood and many other studies. When subjects in MacKay's study shadowed a lexically ambiguous sentence such as "They threw stones toward the bank yesterday", a semantically related word such as *river* presented simultaneously with *bank* on the unattended channel automatically influenced which meaning of the ambiguity they perceived, even though the subjects remained unaware of and unable to report what these unattended words were. Unconscious semantic processes (priming) clearly influenced what meaning entered awareness in this study.

Moreover, when two unattended words, e.g., *river* and *shore*, both related to the same meaning of the ambiguity were presented, the effect was greater than when either word was presented by itself. However, the effects of two unattended words denoting conflicting interpretations of the ambiguity, e.g., *money* and *river*, automatically cancelled each other out, so that the probability of perceiving the two interpretations remained unchanged, as if no words whatsoever had been presented. These findings provide evidence for the inflexible, automatic, and predictable nature of unconscious processing (priming).

Studies of "perceptual defence" (see Dixon, 1981, for extensive examples), where stimuli presented too briefly to enable conscious recognition nevertheless influence other behaviors, also illustrate perception without awareness, as do physiologically oriented studies such as Weiskrantz, Warrington, Sanders, and Marshall's (1974) demonstrations of "blindsight": following lesions to the visual cortex, patients are unable to report the presence of objects falling within large areas in the visual field (called scotomas). However, only verbal responses exhibit this deficit: blindsight patients can quickly and accurately point with their hand or move their eyes toward objects presented briefly within this "blind" region, even though verbally they continue to insist that their consistently accurate manual responses are only guesses. The lesion has dissociated the visual system representations for locating objects with the hand or eyes from the language system representations that enable conscious verbal description.

Action Without Awareness

As expected under the node structure theory, awareness neither causes nor consistently accompanies behavior in available data. For example, we can use unconscious processes (priming and activation) rather than conscious processes to maintain behavior, as when we orient ourselves in space and perform actions such as walking using visual cues that never enter our awareness (Lee & Lishman, 1974). Moreover, even when people *do* become conscious of the stimuli that trigger or guide their actions, *awareness of the stimuli is unnecessary for action.* As James (1890) pointed out, awareness cannot *cause* behavior because actions can precede rather than follow awareness: when pricked with a pin we withdraw the finger first and become aware of the pain later.

Perception-Production Errors: Deep Dyslexia

Because MacKay (1982, and 1987b, pp. 120-121) deals in detail with the effects of unconscious processes (priming) on everyday errors in perception and production. I will examine a somewhat different example here, deep dyslexia. Due to cerebral injury, deep dyslexics produce semantically similar word substitutions that are indistinguishable from the word substitutions of normal individuals except that the dyslexic cannot immediately correct the errors and makes them when reading printed words, misreading the word *table* as *chair*, or *uncle* as *aunt*, for example. The "near miss" nature of the target and error concepts indicates that the correct (visually presented) word must have received unconscious semantic processing (priming), but could not become activated to determine the response, perhaps because the lesion had selectively impaired the return connection from the sequence node to this particular content node. As a result, the target content node, say, *table*(noun), could not become activated, but nevertheless passed on priming to its semantic relative, *chair*(noun), via connections within propositions such as *Tables and chairs are furniture*, so that *chair*(noun) therefore became activated in error as the most primed node in the domain.

Differences Between Conscious Versus Unconscious Processes in Perception and Action

The second part of the three-body problem, part 2, is: what accounts for the differences between conscious versus unconscious processes? Conscious processes have been shown to differ from unconscious processes in six ways that make theoretical sense under the node structure theory; extensiveness, predictability, rate, flexibility, serial versus parallel character, and level of processing.

Extensiveness of Conscious Versus Unconscious Processing

Conscious processing is normally much more extensive than unconscious processing. Whereas unconscious processing is limited to the old and familiar, e.g., the meanings and syntactic categories of familiar words, conscious processing also extends to what is new, e.g., the particular conjunction or relation between words and the implications of this conjunction in the particular situation in which the word is spoken (MacKay, 1973a).

Predictability of Conscious Versus Unconscious Processing

With competing sources of input, priming is unconscious and predictable: familiar aspects of both input sources automatically become primed. However, activation and awareness are subject to effects of motivation which are unpredictable. By selectively directing attention (e.g., applying activating mechanisms at lower than normal levels), higher-level nodes representing one input source but not the other will become activated and introduce pertinent novelty, the precondition for awareness.

The Flexibility of Conscious Versus Unconscious Processing

Whereas unconscious priming spreads automatically up to some fixed level, the level at which conscious processing begins is flexible rather than fixed and automatic. We *normally* only become aware of higher-level aspects of an input, i.e., the sentential and discourse levels in the case of language, and objects and ego space in the case of vision (Marcel, 1983), and we *normally* remain unaware of the sensory and lower-level conceptual events that play a role in determining that awareness, e.g., phonemes. As we have seen, however, consciousness can begin at a lower than normal level when an input is attended to, novel, degraded, unexpected, or unfamiliar.

Serial Versus Parallel Nature of Conscious Versus Unconscious Processes

Whereas unconscious processes such as priming are fundamentally parallel in the node structure theory, awareness within a system is fundamentally sequential. The way that subjects become aware of the meanings of lexically ambiguous sentences clearly illustrates this sequential character of awareness: when searching for the two meanings of ambiguous sentences, subjects in MacKay and Bever (1967) perceived first one meaning, then the other, because only one node at a time can receive most priming and become activated in any given domain. But even though only one interpretation of an ambiguity becomes conscious at a time, both meanings receive *unconscious* processing (priming) simultaneously and in parallel (see Swinney, 1979; MacKay & Bever, 1967).

Experiments demonstrating effects of the unseen meanings of an ambiguous word on the interpretation of subsequent words further illustrate the parallel nature of priming. For example, Marcel (1983) tachistoscopically presented an ambiguous word such as *palm* followed by a patterned mask that prevented recognition or even better-then-chance guesses as to whether any stimulus whatsoever had preceded the masking pattern. The dependent variable was lexical decision time for a subsequent, consciously recognized word, either *maple* or *wrist*. The results showed that *palm* facilitated lexical decisions for both of these related words. The pattern mask clearly prevented conscious awareness (i.e., prolonged activation of lexical and phonological nodes representing) of *palm*, but did not prevent the priming that spreads unconsciously and in parallel from *palm* to words related to its two meanings (for a replication, see experiments 5 and 6 in Fowler, Wolford, Slade, & Tassinary, 1981).

The Rate of Conscious Versus Unconscious Processes

One implication of the fact that consciousness requires prolonged activation is that conscious processes are necessarily slower than corresponding unconscious processes such as priming and self-inhibited activation. This relative slowness of conscious processing explains why subjects searching for the two meanings of an ambiguous sentence take so long to become *aware* of both meanings (MacKay & Bever, 1967), even though both meanings are processed *unconsciously* (i.e., primed) shortly after reading the ambiguous word (Swinney, 1979).

Relations Between Awareness, Attention, and Practice in Perception and Action

I turn now to part 3 of the three-body problem; relations between awareness, attention, and practice in perception and action.

Relationship Between Consciousness, Learning, and Practice

Because the node structure theory postulates two fundamentally different types of learning, engrainment learning (see MacKay, 1982, 1990) and commitment learning, and only one type (commitment learning) determines awareness, the relationship between learning and awareness is relatively complex. Both types of learning are automatic, requiring neither intention nor volition. However, engrainment learning consists of unconscious increases in linkage strength that result from repeated first-order priming and activation of nodes via already existing connections (see MacKay, 1982, 1990) and is only very indirectly related to what enters or fails to enter awareness. Commitment learning, on the other hand, concerns the process of forming or "committing" new connections and gives rise to conscious awareness.

Distinguishing between these two types of learning in the theory explains two seemingly contradictory but persistent observations on the relation between practice, learning, and awareness: the fact (discussed on p. 279) that we learn and become conscious of mental contents *encountered for the first time* (commitment learning), and the fact that *repetition* (practice) often improves behavior *without* *awareness.* A recent example of the latter appears in Marcel (1983; see Hebb, 1963; and MacKay, 1981, for other examples). Words that are so effectively masked as to be unreportable facilitate lexical decisions for semantically similar words (see p. 299), and Marcel (1983) showed that repeating these unreportable words increased the facilitatory effect. Specifically, Marcel (1983) recorded lexical decision time for a word that followed 2-20 repetitions of a semantically similar but unreportable (masked) word, and found that lexical decision times improved systematically with repetition of the unreportable (masked) word up to an asymptote resembling that of the priming function in Fig. 2. Under the theory, the increased facilitation reflects engrainment learning: repeating the unreportable word improved its linkage strength and transmission of priming to connected nodes up to some asymptote, all in the absence of awareness.

Retrieval and Awareness

Nodes undergoing prolonged (conscious) activation prime and enable activation of nodes representing related concepts. This explains why it helps for people to consciously remind themselves of tasks that remain to be performed (Mandler, 1985): conscious reminders make remembering more likely by increasing linkage strength (engrainment learning), and by keeping relevant (connected) concepts highly primed and ready to be activated when conditions appropriate for retrieval or action appear.

Effects of Level in a Hierarchy

The inverse relationship between awareness and practice or repeated retrieval is one of the few generally agreed upon pretheoretical phenomena in the field: when our behavior becomes more skilled as a result of practice, we become progressively less conscious of how we execute it. Consciousness cannot occur when a perceptual or behavioral process has received so much practice as to become fully automatic (Sokolov, 1963; Shiffrin & Schneider, 1977). However, the usual explanation of this phenomenon, that consciousness constitutes a limited resource that must be reserved for unpracticed or nonautomatic processes, is at best circular and at worst untenable (see Allport, 1980).

Practice also plays a role in some of the well-known limitations of conscious processing, such as the fact that only the products of a mental activity enter consciousness, not the processes (Mandler, 1985). This limitation reflects the fact that only high-level content nodes normally undergo prolonged activation and give rise to consciousness under the node structure theory; awareness cannot arise when content, sequence, and timing nodes are highly practiced and automatically activated.

Effects of Action on Attention and Awareness

The node structure theory predicts profound effects of action on attention and awareness: when an action such as speech production must be based on inputs arriving via an attended channel, awareness of inputs via *unattended* channels should drop drastically under the theory. For example, compare two versions of a dichotic listening task where subjects respond as quickly as possible to a target word arriving at either ear: an *action* version where subjects produce (shadow) the input to one (attended) ear, and a *listening* version where subjects simply listen to that ear without shadowing its content. Under the node structure theory, detectability of the target word should be higher in the listening condition than in the action condition. Of course such a difference might be attributable to acoustic masking of unattended inputs by the shadowing output, but the node structure theory predicts this same difference without the possible masking artifact when shadowing is achieved by internal speech or mouthing (silent articulation) rather than overt speech. The reason is that under the principle of higher-level activation, perception (as in simple listening) does not engage the activating mechanism (sequence and timing nodes) for lower-level systems, and bottom-up input can automatically make the target node most primed in its domain, regardless of the target's channel of origin. Repeated application of the activating mechanism to the target domain will therefore ensure activation and awareness under the most-primed-wins principle. However, production (including silently articulated shadowing) must engage the activating mechanisms for lower- and higher-level systems representing the *attended* input, so that arrival of the target via the *unattended* channel will not guarantee most-primed status for the target node because of the boost in priming that nodes representing attended inputs will receive. As a result, shadowing will greatly interfere with detection of targets presented to the unattended ear.

Conclusion

The three-body problem is complex: an adequate account of relations between perception, action, and awareness calls for a general theory of mind with a scope ranging from errors, sequencing, and timing in behavior, to learning, memory, and amnesia. And if the present account is correct, awareness mechanisms in such a theory will be inseparable from mechanisms for representing novelty, and mechanisms for explaining selective and divided attention will be inseparable from mechanisms for perception and action in general.

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