From Input to Intake: Towards a Brain-Based Perspective of Selective Attention

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Anatomy is destiny.
(Freud, attributed)

From a neurobiological perspective, the present paper addresses (1) the input-intake distinction commonly made in applied linguistics, and (2) the role of selective attention in transforming input to intake. Primary emphasis is placed on a neural structure (the nucleus reticularis thalami) that appears to be essential for selective attention. The location, connections, structure, and physiology of the nucleus reticularis thalami are examined to illustrate its critical role in information processing. By orchestrating the selection and enhancement of relevant sensory input, the nucleus reticularis thalami acts as a "conductor" of neural systems involved in learning. It is argued that investigations of brain structures such as the nucleus reticularis thalami provide a more fundamental understanding of language acquisition mechanisms.

INTRODUCTION

First and second language learners must interact with the environment to acquire the target language. Interaction with the external milieu continually shapes the internal milieu supporting the mental systems of language, cognition, and social meanings (Hatch & Hawkins, 1987). In the neurobiological perspective adopted by the present paper, language is viewed as a multimodal sensory enhancement system (Jacobs, 1988), that is, a system that depends

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on the primary senses (i.e., audition and vision) for the linguistic *and* contextual information they bring into the brain, where meaning is derived by comparing incoming sensory information with extant neural structures formed by experience. Learning, including language learning, thus involves the experience-dependent generation or modification of enduring internal representations (Dudai, 1989; cf. Jacobs & Schumann, 1992).

The interaction between the learner and the environment not only takes place in the context of an "action dialogue" (Bruner, 1975, p. 284), but also within a localized situational and larger socio-cultural context (cf. Ochs, 1982; Ochs & Schieffelin, 1984; Schieffelin & Ochs, 1986; Ochs, 1988; Schieffelin, 1990). Language learners are continually exposed to far more information than they can possibly process. Thus, a major concern for language acquisition researchers is how language learners selectively attend to information in the environment, that is, how *input* becomes *intake*. From a neurobiological perspective, the present paper first discusses the distinction between input and intake that is commonly made in applied linguistics. Because the input-intake distinction is intimately related to the concept of selective attention, we briefly explore the role of selective attention in modulating information flow. Finally, we attempt to provide a more fundamental understanding of selective attention by presenting a neural structure that appears to be involved in transforming input into intake.

INPUT AND INTAKE: THE NEED FOR SELECTIVE ATTENTION

In second language acquisition (SLA), input and intake are characterized as both objects/products and processes. When input is characterized as an *object*, it may be equated with the source of information to which the learner is attending. This source of information cannot be limited to exposure of a linguistic nature because, even though a great deal of sensory information is ignored or discarded as irrelevant by the brain, it is never clear exactly what the individual is perceiving. When input is characterized as a *process* (Young, 1988), it appears to overlap with the psychological constructs of *comprehensible input* (Krashen, 1981, 1982, 1985) and *intake* (Corder, 1967), which have been hypothesized to "explain" how learners "internalize" the linguistic patterns available in the input. These constructs are presumed to account for the portion of the input that actually makes it into the learner's head as an organized and retrievable form of knowledge. The i in Krashen's well-known metaphor, i + 1, is an attempt to characterize the state of the learner's brain at a given point in acquisition, but it has been severely criticized for failing to explain the acquisition "mechanisms" involved (Gregg, 1984). Chaudron (1985) has elaborated on these "mechanisms" by suggesting that intake is a complex process (rather than a product) involving the perception and encoding of input, followed by integration of linguistic information into the developing grammar.

As helpful as these attempts to describe input and intake may be, they remain abstract characterizations of learner behavior and, as such, reveal nothing of the underlying mechanisms involved (Jacobs & Schumann, 1992). The present neurobiological perspective attempts to describe underlying *neural* mechanisms responsible for processing input and intake. Thus, in the present perspective, *input* is viewed as the *object* of the learner's attention and *intake* is viewed as the *product* of information processing in the brain, which is discussed below.

Selective attention: Modulating information flow

Language learning requires that the brain's processing systems have access to relevant input. This is accomplished through selective attention, a phenomenon whereby an individual directs attention towards and maintains attention on the stimuli of relevance. The present section will describe selected conceptualizations of the attentional process: the neurobiological concepts of early and late selection, and the psychological concepts of bottom-up and top-down processing.

Neurobiologically, meaning is constructed from the interaction of sensory information (i.e., the "external context") with prior knowledge as it is organized in the brain (i.e., the "internal context") (Jacobs, 1991). It is the internal context that influences an individual's selective attention and subsequent understanding of input. Presently, there is disagreement about how the internal context influences selective attention because, theoretically at least, its influence may be manifested in one of two ways: early selection or late selection. With regard to early selection, the internal context restricts the capacity for sensory processing, necessitating a "filtering" of input based on simple characteristics of the stimulus, prior to semantic encoding (Broadbent, 1958; Edelman, 1989; LaBerge, 1990; Mangun & Hillyard, 1990; Corbetta, Miezin, Dobmeyer, Shulman & Petersen, 1991). With regard to late selection, the internal context sets no limit on sensory processing, allowing selective attention to occur simultaneously with or following semantic encoding (Edelman, 1989; Mangun & Hillyard, 1990; Corbetta et al., 1991). Whether it occurs early or late, selective attention is the outcome of multiple mechanisms mediating action directed toward achieving goals or satisfying criteria set by the individual's internal context (Treisman 1960; Treisman & Gelade, 1980; Crick, 1984; Allport, 1987; Neumann, 1987; Edelman, 1989).

Psychologically, there are two Vygotskian based theories for how patterns in stimuli may be recognized and sensory events are given meaning: bottom-up processing and top-down processing (Rogoff, 1990). Bottom-up processing suggests that a new stimulus is examined by its basic elements or features. This processing is "bottom-up" because the stimulus must be analyzed into specific features or building blocks before being assembled into a meaningful pattern. Top-down processing examines a stimulus, not by discrete feature analysis, but by rapid pattern organization, making use of situational context. Both neurobiologically and psychologically, learning thus begins with a perception and focused attention on a stimulus.

Although psychological theories and information processing models have made significant progress in explaining the role of selective attention in learning (Shiffrin & Atkinson, 1969; Craik & Lockhart, 1972), they cannot adequately explain *how* one attends to appropriate stimuli nor do they address the neural mechanisms involved in selective attention. However, a brain-based model can. Just as Krashen's (1985) "affective filter" has found neural correlates in the work of Schumann (1990, 1991), selective attention appears to fall within the domain of a neural structure known as the nucleus reticularis thalami (NRT). The following section describes the NRT and discusses its involvement in selective attention.

A PUTATIVE BRAIN STRUCTURE FOR SELECTIVE ATTENTION: THE NUCLEUS RETICULARIS THALAMI

Numerous networks involved in selective attention have been identified (Posner, Inhoff, Friedrich & Cohen, 1987; Robbins & Everitt, 1987; Desimone & Ungerleider, 1989; LaBerge, 1990; Mangun & Hillyard, 1990; Posner & Peterson, 1990; Corbetta et al., 1990, 1991; Cohen & Rafal, 1991). However, it remains unclear how these multiple systems work in concert. Although the present paper will not elaborate on the cohesion of this "cerebral symphony" (Calvin, 1989), it will discuss a neural structure that seems to function as its "conductor," coordinating the expression and salience of the various instruments in this orchestra. The "conductor" is the nucleus reticularis thalami (NRT).

The NRT is part of the thalamus, a structure through which all sensory information, with the exception of olfaction (= the sense of smell), must pass before being further processed in the region of the brain known as the cerebral cortex (Figure 1). The NRT's involvement in selective attention is not surprising because it appears to share both morphological and functional characteristics with the brainstem reticular formation (BRF), a diffuse collection of neurons with far-reaching connections throughout the brainstem.[1] Morphologically, NRT neurons (= nerve cells) resemble those of the BRF in terms of size and general branching patterns (Carpenter & Sutin, 1983). Functionally, both NRT and BRF neurons are involved in arousal (Carpenter & Sutin, 1983; Scheibel, 1984). The BRF responds to sensory stimulation and, via pathways that ascend through the brainstem to the cortex (in particular the lemniscal and the ascending reticular activating systems), exerts its influence over broad areas of the cortex, evoking arousal responses (Carpenter & Sutin, 1983). En route to the cortex, the ascending pathways project upon (= make connections with) regions of the thalamus and thus involve the NRT (Carpenter & Sutin, 1983, Steriade, Jones & Llinás, 1990).

To illustrate the NRT's role in selective attention, the following sections sequentially discuss its (1) location, (2) connections, (3) structure, and (4) physiology. The location and connections of the NRT underscore its essential involvement in selective attention. How the NRT participates in selective attention becomes clear when one examines its structure and physiology.

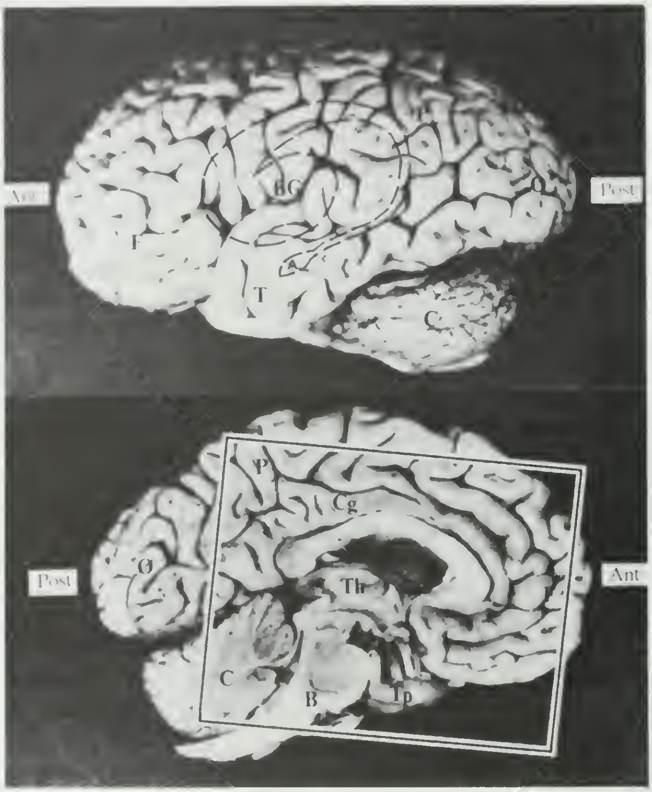


Figure 1. Photographs of the left hemisphere of the human brain. Lateral (top photo) and medial (bottom photo) views demonstrate the relative position of the cerebellum (C) and the four major lobes of the cerebral cortex: frontal (F), parietal (P), occipital (O) and temporal (T). In addition to these regions, **the lateral perspective** illustrates the relative position of the basal ganglia (BG) and amygdala (A), both of which are deep to the cerebral cortex. **The medial perspective** reveals the relative position of the thalamus (Th), cingulate gyrus (Cg), brainstem (B), and the temporal lobe (Tp). Running throughout the brainstem is the diffuse network of cells known as the brainstem reticular formation (BRF) (not shown). The framed area in the medial view outlines the portion enlarged for Figure 2. Ant = Anterior, Post = Posterior.

Location

As mentioned earlier, language acquisition is dependent on the primary senses (i.e., audition and vision) for bringing linguistic and contextual information into the brain. All sensory information entering the brain, with the exception of olfaction, passes through the thalamus, where it is associated and synthesized, before proceeding to the cerebral cortex. The cerebral cortex, which processes and responds to sensory information, is traditionally divided into four major regions, or lobes, each of which serves a specific processing function (Figure 1). In order for sensory

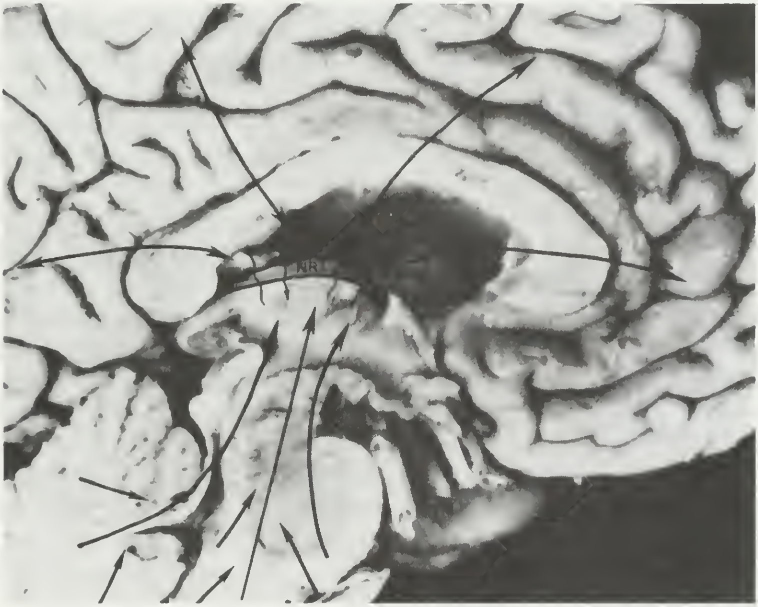


Figure 2. Enlarged view of the medial surface of the human brain as framed in Figure 1. This perspective highlights, somewhat schematically, the position of the nucleus reticularis thalami (NRT) on the dorsal portion of the thalamus. By virtue of its position in the center of information flow, all incoming sensory impulses (e.g., from the cerebellum and through the brainstem) must pass through the thalamus and the NRT en route to the cerebral cortex (single headed arrows). There is continual two-way communication between the cerebral cortex and the thalamus (double headed arrows), all of which also passes through the NRT.

information to reach appropriate areas of the cortex, it must be directed there. The thalamus serves this function.

The thalamus consists of several nuclei, or groups of cells sharing the same function. One of these nuclei is the NRT, a sheet-like complex of cells enveloping thalamic nuclei committed to sensory and associative functions (Scheibel & Scheibel, 1966; Jones, 1975, 1985; Skinner & Yingling, 1977; Angel, 1983; Avanzini, de Curtis, Panzica & Spreafico, 1989). As shown in Figure 2, all connections from the thalamus to the cortex (thalamocortical) and back (corticothalamic) pass through the NRT (Jones, 1985). By virtue of its location, the NRT is intimately involved in the modulation of all communication between the thalamus and the cortex. It constitutes a high resolution organic "screen" capable of monitoring and modulating thalamo-cortico-thalamic interactions (Scheibel & Scheibel, 1966), a "screen" that preferentially enhances certain aspects of stimuli and simultaneously attenuates the salience of other input.

Connections

Information is organized topographically in the central nervous system (CNS), which consists of the brain and the spinal cord. In other words, external stimuli are mapped onto the CNS in an orderly fashion. Auditory impulses are mapped tonotopically (i.e., frequency relationships between sounds are preserved from the cochlea of the inner ear to the auditory cortex). Visual stimuli are organized retinotopically (i.e., visual field images on the retina are transferred faithfully to the visual cortex). Tactile and motor information are represented somatotopically (i.e., the relationships between parts of the body are maintained in CNS representations). The brain's topographical organization permits sensory information to be processed efficiently in circumscribed networks dedicated to a particular type of information. The NRT also adheres to a general topographical organization (Jones, 1975, 1985), which helps it to direct in an orderly manner the enormous amount of sensory information ascending to the cortex. The NRT's topographical relationship with the thalamus and cortex is evidenced by the constant, relatively circumscribed regions of the NRT through which thalamocortical and corticothalamic fibers of particular thalamic nuclei cross (Steriade et al., 1990). Regions of the NRT are thereby associated with a thalamic nucleus or group of nuclei (primarily in the upper-most or dorsal portion of the thalamus) and hence a sensory or functional system (Steriade et al., 1990). As thalamocortical and corticothalamic fibers pass through the NRT, the NRT is capable of influencing information flow. The NRT works as a "gating mechanism" (see below), permitting (i.e., selecting) passage of specific information for further processing (Skinner & Yingling, 1977; Yingling & Skinner, 1977; Scheibel, 1987; Steriade et al., 1990).

Regions of the NRT that may be involved with language are implicated in research conducted by Ojemann (1975, 1976, 1984). Using electrical stimulation of the human brain in patients undergoing surgery for intractable epilepsy, Ojemann identified specific areas of the thalamus involved with language, arousal, and verbal memory. Projecting a series of slides on a screen, Ojemann tested his subjects' ability to name and recall objects while electrically stimulating areas of the thalamus. Electrical stimulation acts as a temporary, reversible lesion that helps identify structures involved in a particular function. Four basic types of language disturbances resulted from this stimulation: arrest of speaking, anomia, perseverance, and repetition.[2] These dysfunctions were identified by stimulation of discrete areas of the left thalamus (especially the ventrolateral portion). Within this context, the NRT theoretically acts as a modulator of nerve impulses conducted through thalamocortical fibers (axons) originating in the left ventrolateral thalamic nuclei. The nerve signals passing through the NRT are believed to prime the cortex of the left hemisphere for incoming, linguistically relevant information (Ojemann, 1975).

Many structures besides the cortex are involved in learning. Four structures are of particular interest: (1) the hippocampus, (2) the cerebellum, (3) the basal ganglia, and (4) the cingulate gyrus (Edelman, 1989; Seib, 1990). The *hippocampus*, which is located deep within the temporal lobe, consolidates recently acquired information and is involved in laying down new memories, including spatial and episodic memory (Edelman, 1985; Rolls, 1990; Kandel, Schwartz & Jessell, 1991). The NRT may assist the hippocampus by focusing and maintaining attention on relevant stimuli.

The NRT may similarly facilitate *cerebellar* processing. Traditionally the cerebellum (shown in Figure 1), which sends information to the cortex via the thalamus, has been recognized for its involvement in motor coordination. More recently the cerebellum has been implicated in cognitive functions such as the learning of rote memories (Edelman, 1989; Schmahmann, 1991; Robbins, this volume). To cite one example, Petersen, Fox, Posner, Mintun and Raichle (1989) monitored subjects performing a semantic association task. The task required subjects to generate a semantically-associated verb for a series of nouns. Using Positron Emission Tomography (PET), an imaging technique yielding anatomical-functional correlations, they discovered activation (i.e., increased activity and therefore greater processing demand) in regions of the cerebellum distinct from areas involved in motor tasks. These results strongly suggest "cognitive" functions be added to the cerebellum's well-known sensory and motor repertoire. The *basal ganglia*, which consist of several substructures (caudate, putamen, globus pallidus, amygdala, and claustrum), serve an associative function, connecting sensory and conceptual categorization with motor responses (Edelman, 1989) (Figure 1)[3]. Many basal ganglia interconnections with the cortex are mediated by the thalamus. With a passive presentation of visual words, Petersen, Fox, Posner, Mintun, and Raichle (1989) found that an area of the basal ganglia (the left lateralized area, possibly the putamen) was activated. They concluded that the basal ganglia may be involved in lexical or letter level processing. The NRT may influence processing in the basal ganglia by indirectly modulating information traveling between the cortex and the basal ganglia (particularly to the putamen and caudate nucleus) (Carpenter & Sutin, 1983).

The NRT also works in concert with the *cingulate gyrus*, which is part of a somewhat diverse collection of brain areas known as the limbic system (Figure 1). The limbic system contributes to emotion, memory, and the coordination of value-dependent states (Kandel et al., 1991; LeDoux, 1992). Petersen and colleagues (1989) suggest that the cingulate gyrus may be involved in response selection. Subjects were asked to perform two tasks: the "generate uses" and the "semantic monitoring" tasks. The generate uses task required subjects to utter semantically associated verbs to a string of visually and aurally presented nouns. This task involved both lexical processing and response selection. The semantic monitoring task required subjects to read a list of nouns and report the proportion of nouns belonging to a particular semantic category (e.g., dangerous animals). Two lists were presented: one with a small proportion of nouns belonging to the target category (i.e., 1/40), and a second with a larger proportion of nouns belonging to the target category (i.e., 20/40). This task required both semantic processing and association. Peterson and colleagues (1989) found increased activity in the cingulate gyrus (particularly its anterior portion) for tasks requiring a high level of attention and response selection. The activated region of the cingulate gyrus corresponded to an area identified through lesion studies as being involved in spontaneous speech. The cingulate gyrus may thus be involved in spontaneous, cortically induced reflex movements (Carpenter & Sutin, 1983; Paxinos, 1990; Lem, this volume).

Although the limbic system is diffuse, it brings together principal pathways connecting thalamic nuclei with several other structures (Carpenter & Sutin, 1983), including (1) the BRF (involved in arousal), (2) the hippocampus (involved in memory), and (3) the amygdala (involved in affective evaluation of stimuli—Schumann, 1990, 1991) (Figure 1). Thus, through both direct and indirect connections, the NRT is in a position to modify critical linguistic processes carried out by the above-mentioned structures. Knowledge of the NRT's location and connections establishes its participation in information flow and suggests a possible role in learning. An examination of the structure of the NRT reveals its function, specifically how it participates in selective attention.

Structure

The NRT modulates communication to and from the cerebral cortex by synapsing (i.e., forming "communicative junctions") with thalamocortical and corticothalamic axons. Because the dendrites (i.e., the receptive branches) of NRT neurons run parallel to the boundaries of the NRT, all thalamocortical and corticothalamic axons must come into contact with these dendrites (Figure 3) (Scheibel & Scheibel, 1966; Jones, 1985). As these fibers pass through the NRT, they continually share information with the dendrites of NRT neurons. Constant communication between the thalamus and the cortex guarantees that NRT neurons receive continuously updated information.

The NRT's ability to monitor information flow is enhanced by filament clusters located at the end of each dendrite (Figure 3) (Scheibel & Scheibel, 1966; Jones, 1985). Just as leaves increase the surface area of a tree, and therefore increase its ability to absorb sunlight, filament clusters increase the dendrite's ability to absorb information (Jacobs & Schumann, 1992).

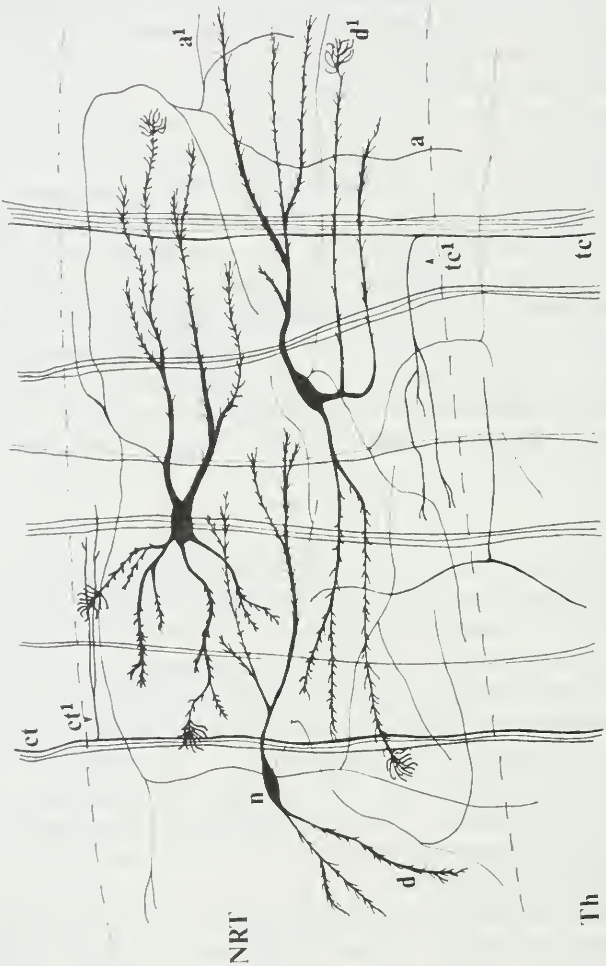


Figure 3. Representative illustration of the nucleus reticularis thalami's (NRT) extensive network of dendrites (d) as they run parallel to the NRT's boundaries. These dendrites end in filament clusters (d^1), which enhance the NRT's capacity to receive impulses from collaterals (tc^1, ct^1) of traversing thalamocortical (tc) and corticothalamic (ct) fibers. Nucleus reticularis thalami (NRT) neurons (n) also emit axons (a), which contribute collaterals (a^1) to the NRT proper before descending toward underlying thalamic nuclei (Th). (Based on Golgi drawings of cat tissue in Scheibel & Scheibel, 1966.)

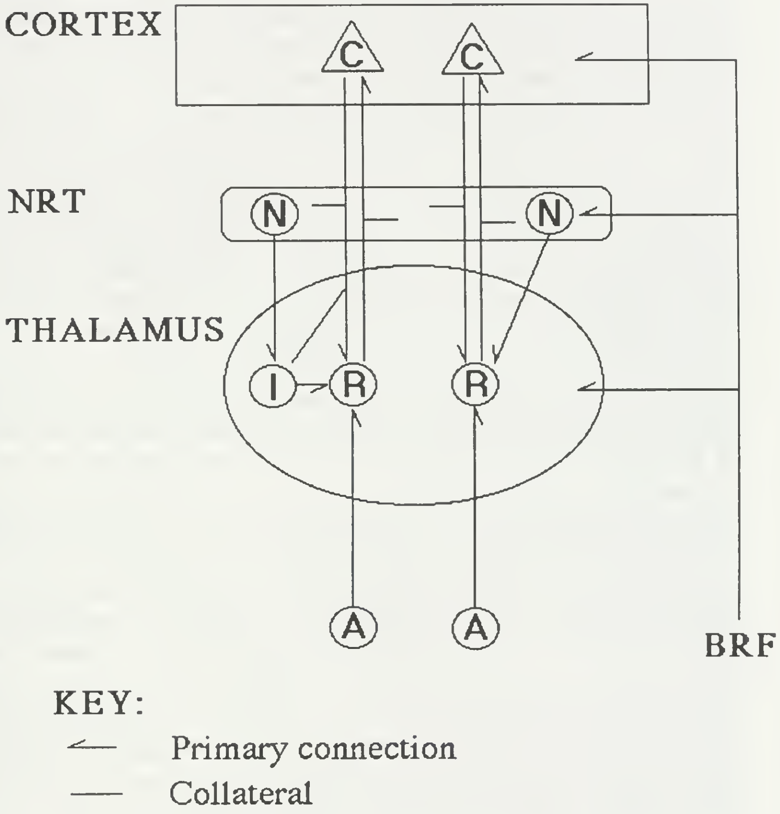


Figure 4. Highly schematized drawing illustrating the major components of the NRT's feedback circuit. Afferent (incoming) information (A) travels to thalamic relay cells (R) from several sources (e.g., the cerebellum and sensory receptors). These thalamic relay cells continually communicate with the cerebral cortex (C). Thalamocortical and corticothalamic communication, however, is differentially affected by thalamic interneurons (I) and NRT neurons (N), which function independently or in conjunction with each other. The brainstem reticular formation (BRF) contributes to this system via projections to the thalamus and NRT neurons en route to the cortex. (Synthesized from Skinner & Yingling, 1977; Scheibel, 1980; LaBerge, 1990.)

The NRT is not only a passive "eavesdropper." It can also intervene in communication between the thalamus and the cortex via its axons. After emitting a few collaterals (= short extensions) that remain within the NRT itself, NRT axons project diffusely to the underlying thalamus (i.e., the dorsal thalamus) (Steriade et al., 1990). NRT axons contact two types of cells in the various thalamic nuclei: relay cells and interneurons. Relay cells are characteristically excitatory, that is, they promote information flow. Relay cells process a single sensory modality, project to specific regions of the cerebral cortex, and receive continually updated information from cortical regions to which they project (Kandel et al., 1991). In contrast, interneurons are primarily inhibitory. They do not project beyond the boundaries of the thalamus, but serve as an inhibitory interface between thalamic cells.

It has been suggested that NRT projections to relay cells and interneurons of other thalamic nuclei establish part of a feedback system which provides a mechanism for focusing attention (Scheibel & Scheibel, 1972; Scheibel, 1981). Other projections contributing to the NRT's feedback circuitry are the collaterals from traversing thalamocortical and corticothalamic axons, as well as projections ascending through the brainstem to the cortex. The primary components of the NRT's feedback system are thus: (1) the thalamic sensory nuclei, (2) the cortex and (3) the BRF (Hobson & Scheibel, 1980; Jones, 1985; LaBerge, 1990; Steriade et al., 1990). The major components of this feedback system continually communicate with each other regarding sensory input. The result of this continual communication is the transformation of selected input into intake. This feedback system, represented schematically in Figure 4, is discussed in greater detail below.

Physiology[4]

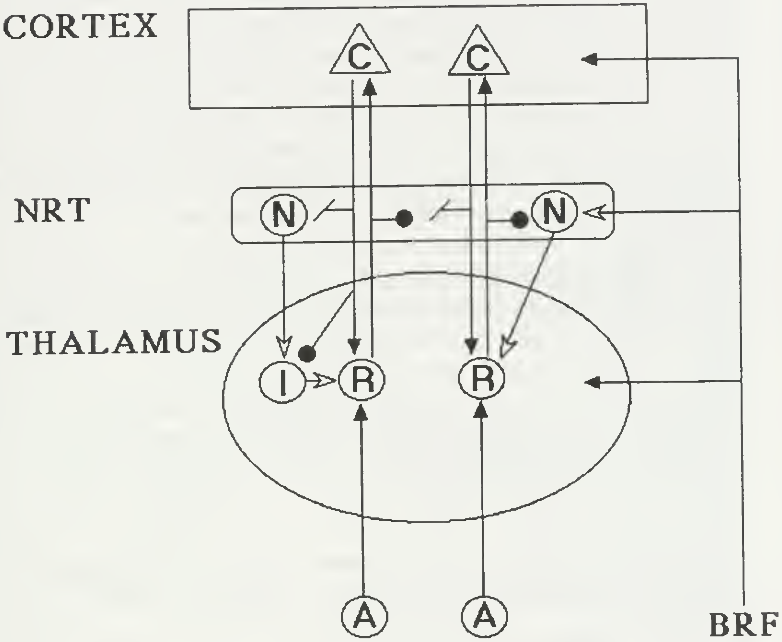
Enhancing the contrast of incoming information. The NRT modulates a topographically organized feedback system. Within this system, the NRT (1) monitors continuously updated communication between interconnected structures (e.g., thalamus and cortex) and (2) promotes the activity of selected neurons as they transmit sensory information to associated regions of the cortex. One of the main functions of NRT modulation is to enhance *contrast* among incoming sensory signals, a phenomenon crucial to CNS activity because neurons respond preferentially to contrast. In general, neurons prefer novel information and tend to cease responding (i.e., habituate) to repetitive and/or non-meaningful stimuli. Habituation helps explain, for example, how a person can forget eyeglasses on his/her forehead. It has also been suggested that because the CNS becomes accustomed to steady states of sensory impulses, pedagogical methods such as Audio-lingualism, which emphasize parrot-like repetition of chained phrases relatively devoid of meaning, have inherent neurobiological shortcomings (Jacobs & Schumann, 1992).

The NRT is active in selectively enhancing and simultaneously suppressing (inhibiting) information that flows through thalamocortical fibers. Ascending impulses from active thalamic neurons are thus enhanced as the NRT attenuates the expression of surrounding neurons, creating a greater contrast or signal-to-noise ratio (LaBerge, 1990). The NRT's inhibitory nature is evidenced by the fact that virtually all NRT neurons contain a chemical (the neurotransmitter gamma-aminobutyric acid, or GABA) that typically has an inhibitory effect.

NRT effects on behavioral states. Most research establishing the inhibitory nature of the NRT uses the electroencephalograph, an instrument that records the electrical activity of the brain (LaBerge, 1990; Steriade et al., 1990). This instrument correlates cell functions with electrical phenomena (= currents). Electrophysiologically, the NRT serves as a "pacemaker" of thalamic activity (Hobson & Scheibel, 1980; Steriade et al., 1990). Thalamic neurons have two distinct electrical discharge patterns, each of which is associated with a different behavioral state. The first is characterized by *synchronous* fluctuations, which are associated with drowsiness and deep sleep. This synchronous activity in the NRT seems to *prevent* sensory information traveling through thalamocortical fibers from being forwarded to the cortex for further processing (Steriade et al., 1990). The second type of current is characterized by *asynchronous* bursts. These are associated with brain-activated behavioral states, such as wakefulness, arousal and rapid eye movement (REM) sleep (Steriade et al., 1990). Asynchronous activity in the NRT enhances the transmission of impulses ascending from the thalamus to the cortex (Steriade et al., 1990), a key aspect of selective attention and learning. Because the NRT projects to virtually all thalamic nuclei, it appears to conduct the rhythmicity of the thalamus, thereby continuously modulating input to the cortex (Skinner & Yingling, 1977).

The NRT as a "gating" mechanism. Selective attention appears to result from the NRT's inhibition of thalamocortical impulses carrying irrelevant information. This selective inhibition implies that the NRT can somehow discriminate between relevant and irrelevant stimuli in a given context (Skinner & Yingling, 1977).[5] As mentioned above, the NRT is part of an inhibitory feedback system which brings together information from the BRF, the cortex, and the thalamic sensory nuclei (Yingling & Skinner, 1977; Scheibel, 1987) (Figure 4). Within this system, the NRT serves as a "gating mechanism." If NRT "gates" are open, information flow to the cortex is promoted; if the "gates" are closed, information flow to the cortex is inhibited (Scheibel, 1987; Steriade et al., 1990). Both the BRF and the cortex (particularly the prefrontal region) affect the NRT's gating function.

Figure 5. Highly schematized drawing representing the physiology of the NRT's inhibitory feedback circuit. Brainstem reticular formation (BRF) projections excite thalamic relay cells (R) and inhibit NRT neurons (N). The BRF can suppress the inhibitory effect of NRT axons on thalamic relay cells, thereby opening the NRT "gate" and promoting thalamocortical information flow. The BRF can also suppress the inhibitory effect of NRT axons on thalamic interneurons (I), allowing thalamic interneurons to resume their suppressive control of thalamic relay cells. In this manner, the NRT "gate" is closed, restricting thalamocortical information flow. The cerebral cortex (C) (particularly the prefrontal region) exerts descending control over cells in the thalamus and the NRT, and has either an excitatory or inhibitory effect. The inhibitory effect of collaterals from corticothalamic fibers on NRT neurons is similar to that of BRF projections. The excitatory effect of corticothalamic collaterals increases the inhibitory effect of NRT axons on thalamic relay cells, closing the NRT "gate" and restricting thalamocortical information flow. The excitatory effect of corticothalamic collaterals also increases the inhibitory effect of NRT axons on thalamic interneurons, suppressing the inhibitory effect of these interneurons, thereby allowing thalamic relay cells to resume their communication with the cortex. The NRT "gate" is thus open, promoting thalamocortical information flow. (Synthesized from Scheibel & Scheibel, 1966; Jones, 1975; Skinner & Yingling, 1977; Yingling & Skinner, 1977; Scheibel, 1980; Scheibel, 1984; Jones, 1985; LaBerge, 1990; Steriade et al., 1990.)



KEY:

← Primary connection - excitatory

⇠ Primary connection - inhibitory

●— Collateral - excitatory

⁄— Collateral - excitatory or inhibitory

BRF influences on the gating mechanism. The BRF regulates attention of a more general, reflexive nature (Skinner & Yingling, 1977; Yingling & Skinner, 1977; Scheibel, 1980). Selective attention driven by the BRF helps explain, for example, how an individual directs his/her attention towards the source of a loud noise. As illustrated in Figure 5, axons ascending to the cortex from the BRF project to the thalamus, facilitating thalamocortical communication. All thalamic nuclei under the BRF's influence send sensory information to their associated areas of the cortex for further processing.

BRF projections to the NRT have an inhibitory effect. When NRT neurons are inhibited, their suppressive control of both thalamic relay cells and interneurons is removed. As *thalamic relay cells* are released from NRT suppression, thalamocortical information flow is promoted. The NRT "gate" is thus opened. As *thalamic interneurons* are released from NRT suppression, thalamocortical information flow is suppressed because the interneurons resume their inhibition of thalamic relay cells. The NRT "gate" is thus closed. The complex sequence of opened and closed gates appears to be responsible for the selective processing of sensory information by the cortex (Scheibel, 1980).

Cortical influences on the gating mechanism. Information flow is regulated not only from "below" by the BRF, but also from "above" by the cortex. This process is known as *descending control* and explains how the cerebral cortex can help select the information it receives from the environment. The cortex, in particular the projections from the prefrontal area to the midline nuclei of the thalamus (the intralaminar, nonspecific thalamic nuclei), tends to regulate more discriminate, voluntary types of attention (Skinner & Yingling, 1977; Scheibel, 1980). Selective attention driven by the prefrontal cortex helps explain, for example, how an individual is able to focus his/her attention on one speaker in a noisy room (i.e., the *cocktail party* phenomenon) and perhaps on specific aspects of linguistic input (Jacobs, 1988).

As for the circuitry itself, collaterals from prefrontal projections to the thalamus can have either a facilitatory or inhibitory effect on NRT neurons. Inhibition of NRT neurons by the cortex is similar to NRT inhibition by the BRF (discussed above). Facilitation of NRT neurons increases the NRT's inhibitory effect on active thalamic relay cells and interneurons. The NRT's direct connections with thalamic relay cells suppress the two-way communication between relay cells and the cortex. In this manner, the NRT "gate" is closed and thalamocortical information is inhibited. However, the NRT is also able to promote thalamocortical information flow through its connections with thalamic interneurons. In this manner, the NRT "gate" is opened. As relay cells are released from the suppressive control of interneurons, thalamocortical information flow is promoted.

Whereas the BRF influences NRT control of more general, reflexive attention, the cortex plays more specifically on the NRT by influencing NRT control of discriminative, voluntary forms of attention.[6] As such, cortical influences are particularly important for the selective attention necessary to attach meaning to sensory signals, including those of a linguistic nature (Jacobs, 1988).

CONCLUDING REMARKS: SPECULATIONS ON THE NRT'S RELEVANCE TO LANGUAGE ACQUISITION

Although a great deal is known about the neurobiology of the NRT, its role in language acquisition is largely speculative. The neurobiological factors presented above strongly suggest the NRT, in concert with other brain structures, plays a crucial role in selectively processing sensory input, including input relevant to language. The key assumption here is that information ascending through the NRT to the cerebral cortex constitutes *intake* (or at least potential *intake*), which is the metaphorical equivalent of integrated and retrievable neural representations. Such neural representations of the external milieu (including knowledge of language) provide the building blocks for continued knowledge (language) acquisition.

In early primary language acquisition, it is likely that the NRT functions in close association with the general arousal mechanisms of the young child. As discussed above, the NRT's role in selective attention constitutes a refinement of the phylogenetically older BRF's general arousal and alerting functions, which are particularly important for a developing brain that is continually exposed to and shaped by a pre- and post-natal environment rich in contextually supported novelty (Jacobs, 1988). The novel environment is essential because stimulus selection is often based on novelty or relevance, as determined by the learner's prior knowledge (i.e., "internal context") (Jacobs, 1991). Because the fetus and neonate are particularly responsive to the acoustic environment (Brazelton, 1986; Turkewitz, 1988; Fernald, Taeschner, Dunn, Papousek, de Boysson-Bardies & Fukui, 1989; Fernald, 1990), and because the brainstem is functionally active at birth (Chugani, Phelps & Mazziotta, 1987), it seems likely that the NRT, under the influence of the BRF, can preferentially direct attention to those aspects of the environment important for language acquisition (e.g., rhythmicity, intonation, frequency variation, and the phonetic components of speech) (Morse, 1972; DeCasper & Fifer, 1980; DeCasper & Spence, 1986).

The prosodic modifications attracting the neonate's attention during this crucial period of brain development exhibit primarily a social-regulatory function (e.g., regulating arousal and attention; expressing communicative intentions of an affective nature such as approval, prohibition, comfort) (Stern, Spieker & MacKain, 1982; Stern, Spieker, Barnett & MacKain, 1983; Fernald, 1991). Towards the end of the first year, however, prosody serves more of a linguistic or analytic function (e.g., focusing attention on objects, enhancing the perceptual salience of individual words, marking linguistic units) (Stern et al., 1983). This may help the child learn new lexical items, parse the speech stream, and identify syntactic units (Gleitman & Wanner, 1982; Peters, 1983; Morgan, 1986; Morgan, Meier & Newport, 1987; Fernald, 1991), thereby laying the foundation for further language acquisition.

Although the BRF maintains its ability to open the NRT "gate" for the lifetime of the organism, the cerebral cortex gradually assumes greater influence over the NRT as the brain matures. Cortical descending control over the NRT would thus assume increasing responsibility in later stages of first language acquisition and in second language acquisition. This is especially true for the descending influence of the prefrontal area, which does not achieve functional maturity until the second decade of life (Chugani et al., 1987). In regulating discrete aspects of attention, the prefrontal cortex provides an individual with a certain degree of control over the sensory (including linguistic) information passing through the NRT gate. After contextualized linguistic input (i.e., external context) is directed to the appropriate cortical area, it may be integrated with extant neural structures (i.e., internal context). In this manner, cortical influences are particularly important for the selective attention necessary to attach meaning to sensory signals, including those of a linguistic nature (Jacobs, 1988).

In conclusion, several neural structures work in concert to manage the overwhelming array of environmental input available to the language learner by selecting and enhancing relevant information to augment previously stored knowledge. These brain regions appear to be coordinated by the NRT which, on the basis of its structure and location, is ideally suited for the task of monitoring information as it flows to and from the cerebral cortex. Although the claims of the present paper derive primarily from work in nonhuman animals, the fundamental neural principles presented here extend to humans without difficulty (Jacobs & Schumann, 1992). The NRT's posited role in language acquisition is at present neither directly observable nor testable. Nevertheless, the present discussion demonstrates that neurobiology provides plausible mechanisms (rather than metaphors) for understanding how learners internalize linguistic patterns available in input.

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NOTES

[1] The brainstem reticular formation (BRF) is one of the oldest structures in the brain and is essential for the organism's survival. Neural pathways ascending to the cortex contribute collaterals to the BRF, providing it with continually updated information. Some of these collaterals maintain their sensory specific modality and serve as sensory relay systems. Other collaterals lose their sensory specific identity, but acquire the capability to activate electrocortical currents characteristic of the brain's attentive or aroused state.

[2] *Arrest of speaking* refers to the subject's inability to speak at all during stimulation. *Anomia* refers to the inability to name objects during stimulation. *Perseverance* refers to the repetition of the object's correct name or first letter of the object's name during stimulation. *Repetition* refers to the repeated utterance of a wrong word during stimulation.

[3] Although the amygdala is phylogenetically associated with the basal ganglia, it is functionally associated with the limbic system (Kandel et al., 1991).

[4] For the sake of clarity, this section oversimplifies the physiological story considerably. A more detailed discussion of the physiology can be found elsewhere (e.g., Skinner & Yingling, 1977; Yingling & Skinner, 1977; Scheibel, 1984; Steriade et al.,1990).

[5] It is extremely difficult to ascertain precisely what input is "relevant" to the learner because relevance is determined by the complex interplay of many factors, including (1) the internal context of the learner, (2) the external or situational context, and (3) the period of development during which the individual is exposed to a given input.

[6] *Descending control* can be clarified by example. When an individual watches television, the BRF's general, reflexive influence is apparent when attention is captured by a sudden change of scene, unexpected action, or fluctuation in volume. The descending control of the cerebral cortex is manifested when an individual manages to maintain attention, despite drowsiness, in order to comprehend key elements of the program.

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