Memory and Control of Action
Richard A. Magill (ed.)

A THEORY OF THE REPRESENTATION AND ENACTMENT OF INTENTIONS

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This paper develops Stelmach and Hughes' (this volume) concept of intentions into a theory specifying what intentions are, how they're organized and represented in the brain and how they become activated in the real time control of skilled behavior. Intentions code three types of information in the theory: what one is trying to do (the components of an action), the order of the intended components, and the rate at which these components are to be activated. Under the theory, a hierarchically organized set of content nodes code the the intended components of an action, an independently stored set of syntax nodes code their serial order, and a set of timing nodes (also independently stored and controlled) determine the rate at which the intended components are activated.

The theory instantiates principles such as flexible and distributed control, specificity of content, speed-accuracy trade-off and constant relative timing and is illustrated in detail by means of examples from speech production. The theory was also applied to phenomena such as production onset time, automaticity, motor equivalence, and the Stroop effect, and seemed broadly applicable to many other types of skilled behavior.

One can readily agree with Stelmach and Hughes (this volume) that we need new models of intention and attention which are both more specific and more adequate than those developed so far. However, coming up with even one such theory is difficult.By way of illustration, I want to develop Stelmach and Hughes' concept of intentions into a theory specifying what intentions are, how they're organized and represented in the brain, and how they become activated in the real time control of skilled behavior. The detailed examples of how intentions become enacted will come from the most proficient of human skills: speech production (see MacKay, 1981a). In passing, we will see that the theory specifically instantiates principles that both Stelmach and Hughes and Rosenbaum (this volume) have endorsed: principles such as specificity of content, distributed control, creativity in behavior, automaticity in highly skilled behavior. The paper concludes by applying the theory to phenomena discussed by Stelmach and Hughes and Rosenbaum: speech errors, the Stroop effect, production onset time, manual control, automaticity, and flexibility or creativity, in motor control.

The Representation of Intentions: Content Nodes

What do we mean by an intention? To ask about someone's intentions or goals is equivalent to asking them what they are trying to do and the answer to this question in everyday conversations normally depends on the perceived level of uncertainty of the person asking the question (see Welford, 1968). However, there are many equally valid answers to this question. For example, let's say you asked me what I am trying to do at the instant marked by the "asteri*sk". I can answer in terms of muscle movements (I am rounding my lips to form an /s/, in terms of syllables or words (I am uttering the word asterisk), in terms of phrases or sentences (I am completing the phrase marked by the asterisk), in terms of the paragraph (I am illustrating the multifaceted nature of intentions), or in terms of the whole paper (I am building up to a specific representation of intentions).

Such intentions concern the form or components of an action such as producing the /s/ in asterisk. We also have intentions concerning the sequencing and timing of actions. I intend to speak at a certain rate and to produce the phonemes in asterisk in the proper order for example. Here, however, I will restrict my use of the term intention to the form or components of an action and talk separately about the sequencing and timing of intentions.

As both Stelmach and Rosenbaum have observed, the representation of output information is a primary consideration for theories of motor control. I therefore begin with the representation of intentions in the theory (see MacKay (1982) for elaboration). The basic components for representing intentions are content nodes each consisting of one or more interconnected neurons. A content node represents a class of intended actions. For example, speakers of English have a content node for the phoneme /s/ which represents the class of actions corresponding to all the context-dependent ways of producing /s/ in English words, including whispering and shouting.

Interconnections Between Content Nodes

The output system consists of billions of content nodes with complex interconnections between them. For example, the dozens of content nodes for producing a sentence are hierarchically interconnected within each of three systems which are themselves organized hierarchically: the conceptual system, the phonological system and the muscle movement system.

The conceptual system. The conceptual system represents the organization of words into phrases and sentences, and three types of nodes can be distinguished on the basis of their connections in this system: propositional nodes, conceptual compound nodes, and lexical concept nodes. Propositional nodes represent the entire thought underlying a sentence; conceptual compound nodes represent parts of the thought; and lexical concept nodes represent the concepts underlying words. For example, the sentence, "Frequent practice is helpful" has one propositional node, two conceptual compound nodes, and four lexical concept nodes, interconnected as shown in Figure 1.

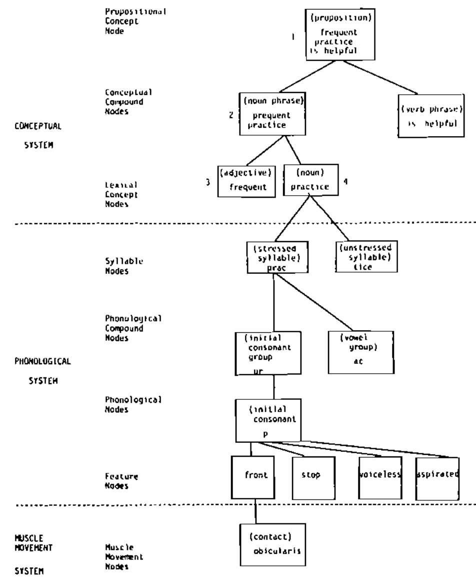

Figure 1: The representation of aspects of the intention to produce the sentence "Frequent practice is helpful": content nodes within the conceptual, phonological and muscle movement systems. (from MacKay, in press)

The phonological system. The phonological system organizes phonemic components into the syllables of words, and four types of nodes can be distinguished on the basis of their connections within this system: syllable nodes, phonological compound nodes, segment nodes and distinctive feature nodes. By way of illustration, Figure 1 represents the structure of nodes underlying production of the syllable prac in practice (see MacKay, 1978 for various sources of evidence supporting this particular node structure). The node labeled prac (stressed syllable) represents the entire phonology of the syllable, the one labeled pr (initial consonant group) represents the consonants preceding the vowel, and the one labeled ac (vowel group) represents the vowel and final consonants. The segment nodes labeled p (initial consonant), r (liquid), a (vowel) and c (final consonant) are connected to distinctive feature nodes (such as front, low, unrounded) which represent simultaneous action specifications analogous to those for arm movement discussed by Rosenbaum (this volume).

The muscle movement system. The muscle movement system represents the organization of muscle movements for articulatory organs such as the larynx, velum and lips. As Rosenbaum notes, the muscle movement system therefore represents just one of many different levels of specification required for executing an intended action.

The Activation of Intentions

Each node has connections with up to several thousand other nodes, each of which is in one of five possible states at any given time: activated, primed (or partially activated), unactivated (or spontaneous level of activation), partially inhibited, and inhibited. Activating a node primes all nodes connected to it, but activation differs from priming in several respects. Activation can be sustained over a specifiable period of time, whereas priming decays rapidly over time to spontaneous level once a connected node is no longer activated. Activation is also all or none whereas priming is graded, varying with how many connections are activated at any one time and how long each connection remains activated.

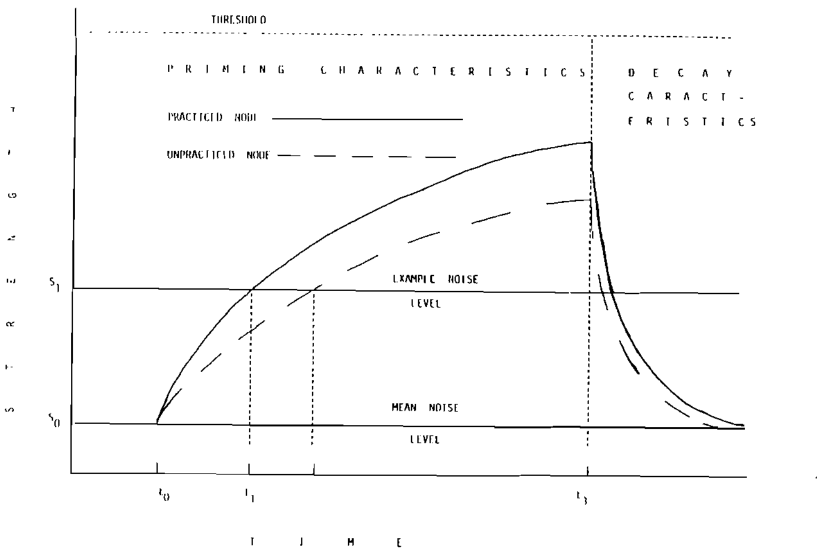

Figure 2. The relation between node strength and time for a hypothetical domain of nodes with resting strength S_o. Priming for a practiced and an unpracticed node is summating over time, beginning at t_o and ending at t_3. (from MacKay, 1982)

Figure 2 illustrates how priming increases over time at the point when a connected node becomes activated (t_o), and decays at the point when input activation ceases (t_3). Note that priming from a single source summates to an asymptotic level below that required for full activation. A triggering mechanism is needed to activate each node.

Figure 2 also illustrates a long-term characteristic of connections: the rate of priming or the amount of priming summation per unit time. Rate of priming increases with practice i.e., the frequency with which a particular connection has been activated in the past (see Figure 2). However, practice only influences specific connections. There are no nonspecific processes in the theory that might be called general motor ability. Predictions concerning an individual's relative skill at different muscle movement activities therefore depend on knowledge of the individual's prior practice. In this sense the theory represents an instantiation of Stelmach and Hughes' dictum that "in biological cognition, everything is content dependent."

Characteristics of the Activating Mechanism.

Figure 2 illustrates some general characteristics of the mechanism for activating nodes (see also MacKay, 1982). The activating mechanism applies to an entire domain of nodes, that is, a set of nodes having identical sequential or syntactic properties. For example, all nodes representing nouns have the same syntactic properties and belong in the same domain. The activating mechanism follows a 'strongest-node-wins' principle, boosting the strongest node in the domain to threshold at some point in time. By applying a specific time following onset of priming the activating mechanism activates whatever node has greatest strength in the domain at that point in time. It therefore controls rate of output: if the activating mechanism is applied at different times following onset of priming for all the nodes in the output system, different rates of output will ensue. As MacKay (1982) demonstrates, this formulation predicts that the relative duration of components of an action will remain constant within wide limits, a phenomenon known as constant relative timing (see Shapiro, 1977). The theory also predicts speed-accuracy trade-off over a wide range of rates (see MacKay, 1982). Errors occur when another "extraneous" node in the domain has greater strength than the node with systematically summating priming at the time when the activating mechanism is applied. This extraneous node will therefore become activated under the strongest node wins principle discussed above, and an error will occur. But since the strength of the intended-to-be-activated node is increasing systematically over time, the sooner the activating mechanism is applied following onset of priming, the greater the probability of activating extraneous nodes whose strength is not increasing systematically but varying randomly over time. As a result, errors will increase with rate of output, independent of type of error or nature of the skill. (see MacKay 1982 for elaboration).

Another characteristic of the activating mechanism is that it can be either applied or not applied to whole systems of nodes. For example, by applying the activating mechanism to all but the muscle movement system, only mental rehearsal occurs: the muscle movement nodes are primed or readied for activation, but no movement ensues. For example, internal speech corresponds to the activation of all of the nodes for producing a sentence except for those in the muscle movement system. (see Figure 1).

A final and most important characteristic of the activating mechanism is that it activates the nodes in proper serial order. As can be seen in Figure 1, activating a node such as the one representing the concept frequent practice simultaneously primes two connected nodes, one representing the concept frequent, the other representing practice. The activating mechanism must somehow have access to the syntax or intended sequence of the output so as to activate the node for frequent before the node for practice, thereby generating the correct sequence in the final output.

The Activating Mechanism: Syntax Nodes

Syntax nodes are an independently stored set of nodes with all of the characteristics of the activating mechanism described above: they organize the content nodes into domains, they activate the strongest node in a domain, they determine the serial order in which the nodes are activated, and they apply independently to the three systems of nodes.

The organizing function. For notational purposes, the content or class of actions a content node represents has been underlined, followed by its syntactic domain in brackets. By way of illustration, the concept node which becomes activated in producing the noun fun is represented fun (noun). The domain (noun) indicates that this node is organized together with other noun nodes and the content fun represents the concept underlying use of the word fun.

Connections between content and syntax nodes (represented here in capital letters) determine the organization of nodes into domains. For example, the syntax node NOUN is connected to the hundreds of content nodes in the domain (noun), thereby organizing noun nodes together with other noun nodes into a single domain. A domain therefore represents a functional relationship shared by a set of nodes and doesn't necessarily correspond to a specific anatomical locus. Several syntax nodes can connect with one and the same content node, which therefore occupies more than one domain. An example is the word practice, which is used with identical meaning as both a noun and a verb. A single content node within the conceptual system represents both meanings by virtue of its connections with the syntax nodes NOUN and VERB. This dual function content node therefore occupies two domains and is represented practice (noun, verb).

The triggering function. The second function of the syntax nodes is to determine what node has the greatest degree of priming in its domain and to activate that node. This triggering function follows naturally from the nature of the connections described above: Activating a syntax node simultaneously primes the entire domain of content nodes connected with it and this priming summates quickly over time. However, the intended-to-be-activated node in the domain is being primed "from above," since its superordinate node (see Figure 1) has just been activated. It is therefore stronger and reaches threshold sooner than other 'extraneous' nodes in its domain and becomes activated.

As a nonspecific activating mechanism, syntax nodes require a gating device to ensure that one and only one content node becomes activated at any one time. The gating device proposed here is an inhibitory link between the content nodes and their corresponding syntax node(s). Once a content node become activated, it briefly turns off its syntax node via the inhibitory link, thereby preventing other extraneous nodes within the domain from reaching threshold. Content nodes must also undergo a period of self-inhibition following activation in order to prevent bottom-up reactivation of higher level nodes (which are identical for input (bottom-up) and output (top-down) processes). This self-inhibitory process may be responsible for the phenomenon of psychological refractoriness discussed by Stelmach and Hughes and others.

The sequencing function. It is important to emphasize that priming is contemporal or nonsequential: an activated node primes all of its subordinate nodes at the same time. The syntax nodes must somehow impose the sequence of activation for every node in an action hierarchy (see Figure 1) and thereby determine the correct temporal sequence for muscle movements in the final output.

The proposed mechanism is as follows: Syntax nodes are connected in such a way as to represent the syntactic rules of a language or any other action system. For example, connections between ADJECTIVE and NOUN represent the rule (adjective + noun) for noun phrases in English. These connections function to make one of two simultaneously primed syntax nodes stronger than the other at one point in time and weaker at another. Lopsided mutual inhibitory connections have exactly this property. For example, with lopsided mutual inhibition between the syntax nodes ADJECTIVE and NOUN for English noun phrases, and simultaneous priming of ADJECTIVE and NOUN, ADJECTIVE will inhibit NOUN more than vice versa and will dominate in strength. However, once ADJECTIVE has been activated and undergoes inhibition via the gating mechanism discussed above, NOUN will accrue greater strength than ADJECTIVE, dominate and thereby become activated next.

The Timing of Intentions

Timing nodes determine the rate and temporal organization of an intended output. Like the syntax nodes, timing nodes perform several functions simultaneously: They provide the mechanism whereby syntax and content nodes are organized into systems and they determine whether and when the syntax nodes become activated.

The Organizing Function

Syntax and content nodes are organized into the three systems discussed above by virtue of their connection to a timing node. There are three timing nodes for producing speech, represented here as the sentence time node, the phonological time node and the muscle time node. The sentence time node is connected to the dozens of syntax nodes representing the sequential rules for English sentences; the phonological time node is connected to the dozens of syntax nodes representing the sequential rules for English phonology; and the muscle time node is connected to the dozens of syntax nodes representing the sequencing of muscle movements for producing English speech sounds.

The Triggering Function

Timing nodes determine the final activation of the syntax nodes within each system (conceptual, phonological and muscle movement), using the strongest-node-wins principle discussed above. When a timing node becomes activated, it simultaneously primes the entire set of syntax nodes connected to it and this priming summates quickly over time. Thus, the syntax node with greatest strength will reach threshold soonest and become activated. Timing, syntax and content nodes are therefore organized hierarchically: a timing node activates the strongest syntax node, which in turn activates the strongest content node.

The Timing Function

Timing nodes constitute the internal clock for determining when to activate the syntax nodes within each system. Their overall pulse rate is under the control of motivational nodes which ultimately determine the rate of output. Each timing node sends out pulses at specifiable intervals, but the mean pulse rate for the three timing nodes differs. For example, the phonologial time node generates more pulses per second than the sentence time node since phonemes are produced faster than words (by a factor of about 5 on the average). However, the three timing nodes are coupled and operate in conjunction: if the sentence time node is speeded up, the phonological time and muscle time nodes must be speeded up proportionally.

The Execution of Intentions: An Illustration

To illustrate how timing, syntax and content nodes interact to determine timing and serial order in the final output, we examine a single example in detail. The example concerns the ordering of the words frequent practice in the sentence, "Frequent practice is helpful." The relevant nodes generating this sequence in the conceptual system are shown in Figure 3: the inhibitory connections with broken lines and the lopsided mutual inhibitory connection with a dotted line.

Activating the content node frequent (noun phrase) simultaneously primes four nodes: two content nodes, frequent (adjective) and practice (noun); and two syntax nodes, ADJECTIVE and NOUN. ADJECTIVE has a lopsided inhibitory link with NOUN, reflecting a learned rule for English word order. Thus, when the sentence time node sends its pulse to the domain of English syntax nodes, ADJECTIVE is stronger than NOUN and becomes activated under the strongest-node-wins principle. Activating ADJECTIVE primes every node in the adjective domain, but frequent (adjective), having just been primed, reaches threshold soonest and becomes activated under the strongest-node-wins principle. Activating frequent (adjective) now inhibits ADJECTIVE since content nodes have an inhibitory link to their corresponding syntax node which prevents other nodes in their domain from becoming activated under the strongest-node-wins principle.

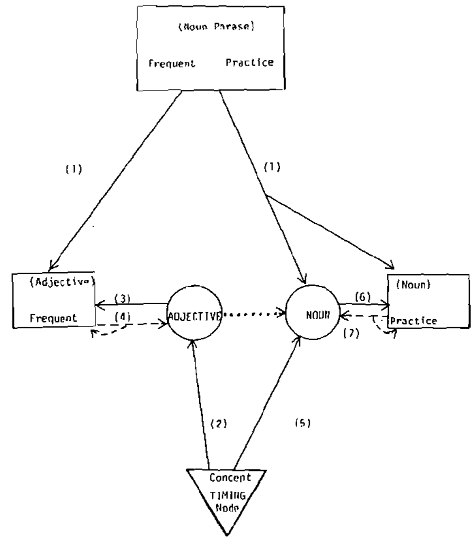

Figure 3. The activation of intentions in producing the noun phrase frequent practice. Order of activation is in brackets, conceptual content nodes in rectangles, syntax nodes in circles, and concept timing node in triangle. (from MacKay, 1982)

All this has taken place following a single pulse from the sentence time node. With the second pulse, ADJECTIVE has become inhibited and no longer inhibits NOUN, which therefore becomes activated under the strongest-node-wins principle.

Activating NOUN primes every noun node, but practice (noun), having been recently primed reaches threshold soonest and becomes activated under the strongest node wins principle. The remainder of the sentence is generated in similar fashion.

Distributed Control, Tuning and Creativity in the Theory

Each content node represents a class of actions and some classes are much broader than those illustrated so far. For example, the words be, is, am and are constitute a single class of actions represented by a single concept node, be (verb) within the conceptual system. Thus, be (verb) has connections to four syllable nodes representing be, am, is and are. These syllable nodes receive connections from concept nodes representing the person (first, second or third) and number (singular or plural) of the subject of the sentence. These nodes prime is (syllable) if and only if the subject is third person and singular, am (syllable) if and only if the subject is first person and singular, and are (syllable), otherwise. One of these syllable nodes will therefore the dozens of syntax nodes representing the sequencing of muscle movements for producing English speech sounds.

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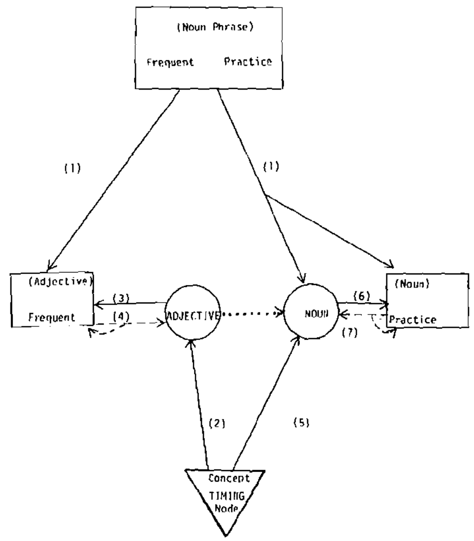

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Verb Agreement

Production of is (syllable) in the example above can be said to represent uncreative or 'warehouse' behavior (after Rosenbaum, this volume). However, speakers of English have the ability to create never previously encountered third person singular forms. For example, the hypothetical child who has only encountered I, you, we or they interpolate in the past, is nevertheless able to produce the never previously encountered he, she, or it interpolates. Creativity of this sort is achieved as follows in the theory. An association is formed between interpolate (verb) and a phonological node representing the regular third person singular form, say S (final consonant). This phonological node receives connections from all other "regular verb" nodes but only becomes activated when it also receives simultaneous (conjoint) priming from the node representing "third person singular subject" (discussed above), giving he, she or its interpolates.

Pig Latin

Pig Latin represents a somewhat different type of creativity involving application of a new serial order rule. Children produce Pig Latin by holding the initial consonant group until the end of a word and then adding ay. Thus children can produce the word motor in Pig Latin as the never previously encountered otormay. Under the theory this type of creativity requires the formation of a new serial order rule for activating the initial syllable of this or any other word. Roughly, the rule is (Vowel Group + remainder of the word + Initial Consonant Group + ay) and requires a new set of syntax nodes to activate these phonological components in that order for any word.

Applications of the Theory

Speech Errors

Speech errors involve an intended-to-be activated node, which is primed from above, and an extraneous node, the source of the error, and occur in the theory whenever the extraneous node has greater strength than the intended-to-be-activated node at the time when the activating mechanism is applied. Since the activating mechanism always applies to a particular domain or syntactic class of nodes, this means that substitution errors will always involve words belonging to the same syntactic category. This explains why errors at every level in the system obey this syntactic category rule: the word level, where nouns interchange with other nouns, verbs with verbs and never nouns with verbs (Cohen, 1966), the morphological level, where prefixes interchange with other prefixes, suffixes with other suffixes, and never prefixes with suffixes (MacKay, 1979), the syllable level where initial consonant clusters interchange with other initial clusters, final with final, but never initial with final (MacKay, 1972), and the speech sound level where vowels interchange with vowels, consonants with consonants, and never vowels with consonants (MacKay, 1972). Even Freudian slips involve words of the same syntactic category. An example is the substitution of battle scared for battle scarred, spoken of a general who is strongly, but covertly, believed to be scared of battle. Under the theory, this error occurred because priming for scared (verb) stemming from the covert belief exceeded that for scarred (verb) at the time when the triggering mechanism was applied to the verb domain.

The Stroop Phenomenon

When subjects are asked to name the color of the ink in which a word is printed, errors are frequently observed when the word spells a color name that differs from the one required. (e.g., the word blue printed yellow ink). As Stelmach and Hughes (this volume) point out, substitution of the printed name (blue) for the color of the ink (yellow) is the most common error. The reason is as follows under the theory: the concept node for the printed word accrues strength faster than that for the ink name, since we have had more practice reading color names than naming colors. As a consequence, the wrong color concept node gets activated when the strongest-node-wins principle is applied to the domain of color adjective nodes.

Production Onset Times

Several recent studies have investigated production onset time, the time to begin a sequence of movement (see Rosenbaum, this volume) Klapp, Anderson and Berrian (1973) investigated the production of one-syllable words, e.g., paint vs. two-syllable words, e.g., paper, which were all 5 letters in length. Klapp et al. first measured the response time from visual presentation of the words until the onset of naming, and found that response time was slightly (15 msec) but significantly longer for two-syllable words, a finding replicated in other studies. In another condition subjects named pictures, and again, response time was longer for two-syllable than one-syllable names. This finding indicates an output effect: number of syllables is a feature of the output in this condition, and not of the input, since pictures don't have syllables.

The present theory explains these findings as due to the time required to prime and activate the nodes underlying the output sequence. Specifically, onset time depends on the number of content and syntax nodes that must be activated prior to the first muscle movement nodes. Production time *per se* is irrelevant under the theory, so that despite the large differences in duration, only small increases in onset time can be expected for a one-vs. two-syllable word, for a one vs. two word sentence, for a one vs. two sentence paragraph and for a one vs. two topic preplanned-lecture (all other factors except output duration being equal). Even length *per se* is irrelevant. For example, the production onset time for pain and paint should be equivalent under the theory (all other factors except length being equal) since the same number of content and syntax nodes must be activated prior to the first muscle movement node for /p/. The nt node and the syntax nodes for ordering (n + t) in paint becomes activated after the first muscle movement node and add to production time, but not to onset time.

Manual Control

The present framework is readily extended to production onset times for manual control e.g., studies such as Rosenbaum (this volume) and Klapp and Wyatt (1976). Klapp and Wyatt (1976) investigated the generation of Morse code sequences by presenting one of four lights to trigger the initiation of one of four response sequences on a Morse Key: dit-dit, dit-dah, dah-dit, and dah-dah. Their dependent variables were production onset time and the time between the first and second responses. Production onset time did not vary with the nature of the second response (dit vs. dah) but was shorter for sequences beginning with dit than for those beginning with dah. The time to initiate the second response (following the first) was likewise longer for dah than for dit. To explain these results, Klapp and Wyatt (1976) reasoned that planning a dit was simpler than planning a dah, that only the first response was planned during production onset time, and that the second response was planned during the inter-response interval following the first. However, another observation contradicted this explanation and indicated that whereas the second press was identical to the first (both dits or both dahs), reaction time was much faster than when one was a dit and the other a dah.

The present theory accounts for all of these findings. Consider first the nature of a dit vs. a dah in the theory. A dit involves three hierarchically organized nodes above the muscle movement level: the highest level "dit node," and two subordinate nodes, one for pressing and another for lifting. However, a dah response is more complex, requiring an additional node for holding the key in contact with the terminal, and a timing mechanism for specifying the duration of this contact phase.

The greater number of content and syntax nodes for producing dah therefore explain its longer onset time (in either first or second position). However, the longer initiation times for sequences with different components, e.g., dit-dah, than with identical components, e.g., dah-dah, reflects a difference in sequencing rules. Identical presses require a simple repeat rule, whereas different presses require more complex sequencing rules such as dit the dah for one sequence, and dah then dit for the other. Retrieving, discriminating, and applying these sequencing rules takes more time than retrieving and applying a repeat rule.

Automaticity

As Stelmach and Hughes point out, automaticity has acquired far too many surplus connotations. However, most researchers concur that automaticity includes the fact that skilled behavior becomes rapid, effortless, error-free, and generated without awareness as a function of practice. So defined, automaticity varies with the level in the system under consideration. For example, when producing a never previously encountered sentence on an unfamiliar topic such as Pig Latin, the choice of meaning to convey is slow, conscious, effortful, and replete with false starts, whereas the choice of phonemes is rapid, unconscious, effortless, and error-free. The question is why.

The answer under the theory is that lower-level nodes receive more practice than higher-level nodes. For example, the highest level concept node underlying production of an expression such as sequential creativity has received little practice, since one rarely encounters the concept of sequential creativity. However, the phoneme nodes for sequential creativity appears in thousands of other words and are activated millions of times over the course of a lifetime. As a consequence, activating the unpracticed higher level node takes considerable time, whereas activating the highly practiced lower level nodes occurs so rapidly that awareness is unlikely and effort unnecessary. (see MacKay, 1981a).

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