JOURNAL OF MEMORY AND LANGUAGE **38,** 28–69 (1998)
ARTICLE NO. ML972544

# H.M.'s Language Production Deficits: Implications for Relations between Memory, Semantic Binding, and the Hippocampal System

Donald G. MacKay

*University of California, Los Angeles*

and

Deborah M. Burke and Rachel Stewart

*Pomona College*

To test the claim that H.M. exhibits a ''pure memory deficit'' that has left his language production intact, we compared the language production of H.M. and controls in three studies. In Study 1, participants described the two meanings of visually presented sentences that they knew were ambiguous, and H.M.'s descriptions suggested a semantic-level production deficit: Relative to controls of comparable age, intelligence, and education, H.M.'s descriptions were significantly less effective, less clear, less concise, and more repetitious at lexical, phrase, and sentence levels of language production. In Study 2, naive judges rated H.M.'s descriptions as less grammatical, less comprehensible, and less coherent than descriptions of controls. Study 3 replicated these results for conversational speech about childhood events that occurred long before H.M.'s operation, his epilepsy, and his epilepsy treatments. Present results contradict stages of processing theories that localize H.M.'s deficit to a storage stage that is independent of processes for retrieving and producing verbal materials, and instead support a distributed-memory theory in which memory storage and retrieval involving verbal materials are inherent aspects of normal language production. 

In 1953, a 27-year-old patient subsequently known as H.M. underwent an operation that sectioned bilateral parts of his hippocampal system. This ''frankly experimental operation'' (Scoville & Milner, 1957) partially alleviated H.M.'s debilitating and otherwise untreatable epileptic condition, but had an unexpected and tragic side effect: a severe amnesia that has hampered acquisition of new episodic and semantic information, reducing H.M.'s life since 1953 to the immediate present and the distant past preceding his operation. Because Scoville's bilateral resection is no longer performed, H.M. is one of the few sources of evidence regarding the bilateral functioning of the hippocampal system in human cognition, and he has become one of the most famous patients in the history of neuropsychology (Ogden & Corkin, 1991).

H.M.'s condition has also had a major impact on theories of memory, and on psychological theory in general. The currently prevailing view is that H.M. suffers from a ''pure memory deficit'' that prevents acquisition or consolidation of new information for explicit recall: Since his operation, H.M. has retained virtually no new verbal information for more

Don MacKay gratefully acknowledges support from National Institute on Aging Grant R01 AG 09755 and from the Max-Planck-Institute for Psychological Research in Munich, Germany. D.M. Burke gratefully acknowledges support from National Institute on Aging Grant R01 AG 08835. The authors thank Drs. Suzanne Corkin and William Marslen-Wilson for generously providing their unpublished transcripts of H.M.'s ambiguity descriptions and conversational speech. We also thank Drs. Suzanne Corkin, Barbara Knowlton, Yvonne Lippa, Michelle Miller, and Nancy Woolf for helpful comments on an earlier version of this paper; Andrew Booty for assistance with Study 2; and Dr. Dale Berger for statistical advice. Rachel Stewart is currently at the Psychology Department Stanford University.

Address reprint requests to Donald G. MacKay, Psychology Dept., University of California, Los Angeles, Los Angeles, CA 90095-1563.

0749-596X/98 $25.00

than a minute or two without continuous rehearsal (Wickelgren, 1968). In contrast, H.M.'s language production (e.g., Haglund & Collett, 1996; Cohen & Eichenbaum, 1993, pp. 49–219), his language comprehension (Milner, Corkin, & Teuber, 1968; Lackner, 1974), and his ability to retrieve memories stored from birth to about age 12–16 (Marslen-Wilson & Teuber, 1975; Rempel-Clower, Zola, Squire, & Amaral, 1996; Sagar, Cohen, Corkin, & Growdon, 1988) are believed to be intact and normal, as are his forgetting functions for encoded information (Freed, Corkin, & Cohen, 1987; Freed & Corkin, 1988).

Nonetheless, evidence regarding H.M.'s intact language production is currently anecdotal in nature, and we had three reasons for examining H.M.'s language production in more detail. One was its general theoretical significance. The second was recent findings that contradict the prevailing view of H.M.'s language abilities. The third was predictions of a recently developed theory that H.M. will exhibit two specific types of production deficit. We discuss these background and theoretical considerations next, followed by details of our experiments. Readers only interested in the latter may skip to the section entitled, *Structure of the Present Paper*.

## GENERAL THEORETICAL SIGNIFICANCE OF H.M.'S LANGUAGE PRODUCTION

How important is the status of H.M.'s language production abilities from a theoretical point of view? At stake are two general and contrasting classes of theories in use within a wide range of neurosciences and cognitive sciences: stages-of-processing theories versus distributed-memory theories. In stages-of-processing theories (see, e.g., Massaro, 1994, for historical review; also Pashler & Carrier, 1996), language and memory employ completely separate units and processes that are organized into four sequentially ordered stages or processing modules: comprehension, storage, retrieval, and production (see Figure 1). That is, people are assumed to comprehend verbal inputs first, before storing and consolidating the products of comprehension in memory. Later, during recall, they first retrieve the stored memory, and then express the memory in language during the final production stage (see, e.g., Gordon, 1989, pp. 196–216).

One attraction of the stages-of-processing framework in Figure 1 is its perfect fit with the currently prevailing view of H.M.'s spared and impaired abilities: If H.M. exhibits a ''pure memory deficit'' with unimpaired language comprehension, unimpaired memory retrieval, and unimpaired language production, then his condition dissociates all four stages of processing, with damage to storage, but to no other processing stage (see Figure 1).

A second attraction is that the processing stages in Figure 1 have been around in various forms since Descartes (see, e.g., MacKay, 1997), and have accumulated a wide range of ostensible support over the past 350 years. For example, Broca (1865) and others argued that language production disorders (e.g., Broca's aphasia) can occur without concomitant deficits in language memory, and vice versa, as if language production involves dissociable units and processes from the storage and retrieval of verbal information. The stages-of-processing assumption that different tasks are processed in discrete, serially ordered stages that overlap in specifiable ways has also led to the development of major methodological approaches or subfields; see, e.g., Poeppel (1996) for a review and critique of ''subtraction procedures'' in PET (positron emission tomography) studies.

A third attraction of the Figure 1 framework is that new stages-of-processing theories are readily created. By simply subdividing the memory stages in Figure 1, theorists have introduced a variety of new modules during the past thirty years, e.g., for episodic versus semantic memory (Tulving, 1983), explicit versus implicit memory (e.g., Graf & Schachter, 1985), sensory and perceptual versus modality-independent memory (Schachter, 1990), procedural versus declarative memory (Squire, 1987, pp. 151–169), reference versus working

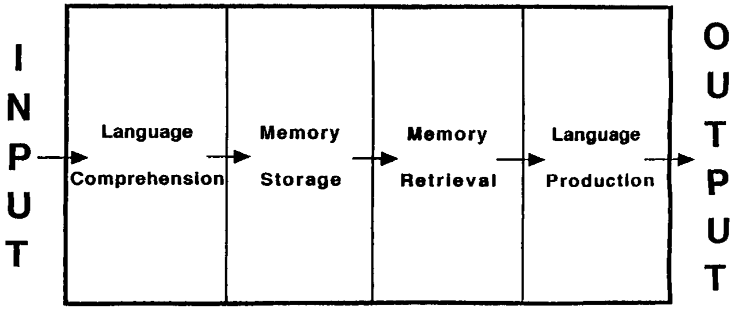


**FIG. 1.** A standard information processing flow chart with sequentially ordered stages for comprehension, storage, retrieval, and production of verbal materials (see, e.g., Gordon, 1989, pp. 196–216).

memory (Cohen & Eichenbaum, 1993, pp. 49–219), short-term versus long-term memory (Atkinson & Shiffrin, 1968), and long-term versus very long-term memory (Squire, 1987, pp. 204–214). Moreover, H.M.'s condition has been cited as central support for all of these more recent modules (see, e.g., Squire, 1987, p. 145; Cohen & Eichenbaum, 1993; and Eichenbaum, Otto, & Cohen, 1994). For example, Atkinson and Shiffrin (1968) and Wickelgren (1975) argued that H.M.'s memory performance provided the best available support for the existence of distinct and separate stores for short-term versus long-term memory (see also Pashler & Carrier, 1996). That is, unlike his long-term retention of new information, H.M.'s memory for verbal events during the past ''minute or two'' seems intact: Corkin (1984) and Corsi (1972) reported a forward digit span of 6, well within normal limits, and Wickelgren (1968) showed that H.M. had normal strength decay functions for immediate ''yes/no'' recognition of verbal and nonverbal materials.

H.M. has also been cited in support of distinct and separate stores for implicit versus explicit memory. Whereas H.M. usually cannot recall information explicitly over extended periods, he generally functions within normal limits on implicit tests of memory, which show effects of prior experience without requiring conscious recollection of the prior experience. Thus, H.M. shows normal facilitative effects of prior processing of a familiar word on subsequent perception of the word (Keane, Gabrieli, Mapstone, Johnson, & Corkin, 1995) or on subsequent production of the word in stem completion and response time tasks (Keane, Gabrieli, & Corkin, 1987; Ogden & Corkin, 1991). However, H.M. is unable to consciously or explicitly recollect his prior encounter with these same words (Keane et al., 1987; 1995). Corkin (1968) likewise demonstrated that across sessions, H.M. gradually became more adept at completing a tactile maze (exhibiting implicit memory resembling memory-normal controls), although he could not recall (explicitly and verbally) having encountered this task before.

The impact of the stages-of-processing framework over the past 350 years in psychology is difficult to overestimate. As Pashler and Carrier (1996, p. 4) note, this framework ''has dominated psychological studies of memory in the past thirty years.'' Virtually all current textbooks in cognitive psychology either explicitly describe Figure 1 as established fact, or implicitly adopt the stages-of-processing framework in structure and content: Like Figure 1, they begin with perception and comprehension, move on to memory, and discuss action last, if at all; and they treat the comprehension, memory, and production of language as entirely autonomous topics (see also Bock, 1996). The assumed autonomy of memory and language also shows up in the many recently developed language production theories that ignore memory and what is known about it (e.g., Garrett, 1992; Kempen & Hoencamp, 1987; Levelt, 1989, p. 8–22), and in the many theories of verbal memory that ignore language production and what is known about it. The exception that proves the rule is working memory theory: The articulatory loop of Baddeley & Hitch (1974) is a construct for explaining the close relations between immediate memory capacity and language production processes related to word length and rate of articulation, but consistent with stages-of-processing assumptions regarding the autonomy of language and memory, the articulatory loop is a ''pure memory'' system that can facilitate language comprehension, but is distinct and separate from language mechanisms (see Gathercole & Baddeley, 1993, pp. 8–32). Recent PET results, however, directly challenge this assumed separation: the articulatory loop ''lights up'' a brain area that also lights up during language comprehension and production in the absence of subvocal rehearsal (see, e.g., Price, Wise, Watson, Petterson, Howard, & Franckowiak, 1994).

Despite the ubiquity of the stages-of-processing framework, and the proliferation of stages-of-processing theories, both explicit and implicit, competitors exist: An entire class of ''distributed-memory'' theories has been developed that can explain basic verbal memory phenomena and detailed aspects of language processing as well (see McClelland, 1985). However, under distributed-memory theories, memory for verbal materials cannot be separated into discrete stages or modules involving differing units and processes, e.g., for short-term versus long-term memory, but depends fundamentally on the strength of connections between millions of neural units or nodes distributed throughout a vast interactive activation network that plays a role in both perception and action, including language production.

This newer and more complex conception of human information processing (see, e.g., Caplan & Waters, 1990; MacKay & Miller, 1996ab; Saffran, 1990) views relations between language, memory, and the hippocampal system quite differently from stage theories. In distributed-memory theories such as Carpenter and Grossberg (1993), Grafman and Weingartner (1996), McClelland (1985), McClelland, McNaughton and O'Reilly (1995), Metcalfe, Cottrell, and Mencl (1992), MacKay (1990), Saffran (1990), Wickelgren (1979), and Woolf (1996), the hippocampal system provides a supplementary input to the cortex that facilitates the formation of new cortical connections required not just for explicit recall, but for the comprehension and use of language. These theories therefore predict deficits in H.M.'s language abilities that contradict stages-of-processing theories and the currently prevailing view of H.M.'s cognitive impairments.

## OBSERVATIONS THAT CONTRADICT STAGES-OF-PROCESSING THEORIES

Judging by H.M.'s responses to direct questions about ongoing events, researchers have generally assumed that H.M. has normal language production abilities (see, e.g., Kesner, 1985), consistent with stages of processing theories. A recent textbook even suggested that H.M. ''can engage in sophisticated conversations'' (Kolb & Whishaw, 1995, p. 359). However, other indications suggest that H.M.'s language production is neither sophisticated nor unimpaired. For example, although H.M.'s verbal output is usually related to the topic at hand, his speech can become markedly tangential, and sometimes assumes a rote or repetitious character (see, e.g., Ogden & Corkin, 1991). Sidman, Stoddard, and Mohr (1968) also raised questions regarding H.M.'s ability to verbally encode his experiences in performing two seemingly nonverbal tasks. In one task, H.M. was trained nonverbally to respond to a single circle rather than to a simultaneously presented ellipse whose circularity increased systematically over 25 trials, and H.M. learned this discrimination relatively quickly for a symbolic reward (a penny for each correct response). However, when asked what he was (successfully) doing, H.M. was unable to accurately describe the task, as if suffering from a language-related deficit according to Sidman et al. The second task involved delayed matching-to-sample for trigrams (three compounded consonants) and ellipses of differing size, and here, H.M. successfully matched the trigrams, but not the ellipses, as if he was unable to verbally label an ellipse as, e.g., ''next-to-largest'', and rehearse the label during the delay interval. Sidman et al. concluded that H.M.'s memory deficit may stem in part from an inability to encode his experiences verbally (a stages-of-processing argument).

However, Sidman et al. (1968) did not compare H.M. with memory-normal controls on this task, making it unclear how unusual H.M.'s verbal encoding performance should be considered. The Sidman et al. procedures also failed to rule out a ''pure memory'' explanation of their data. Consider H.M.'s (p. 248) answer to Sidman's question of how he had earned his pennies in discriminating ellipses from circles: ''Well, I pressed matching up to that would be exactly alike of, uh, well, crosses. . . .'' (there were no crosses). Although this unfocused, ungrammatical, and difficult to understand answer might suggest a language encoding or language production deficit, or both, another activity intervened between H.M.'s discrimination behavior and his answer. Sidman first asked H.M. to count his pennies, a procedure that confounds H.M.'s memory problem with his hypothesized verbal encoding problem: H.M. may have forgotten how he had earned the pennies.

Unlike available data on language production, recent evidence on H.M.'s language comprehension is neither anecdotal nor ambiguous, and contradicts the view that H.M. has a ''pure memory deficit'' that completely spares his language comprehension. MacKay, Stewart, & Burke (in press) reported more than ten sources of data indicating that H.M.'s ability to read and comprehend short, syntactically simple sentences is impaired relative to memory-normal controls matched with H.M. in intelligence, age, and educational level. In addition, H.M. often failed to follow experimenter requests, as if he did not understand them, and he frequently generated free associations and unusual pronoun uses, as if he did not understand what he himself was saying. Likewise consistent with a comprehension deficit, H.M.'s ability to comprehend sentences was worse than ''coin-toss'' levels of accuracy (50%) in a two-choice discrimination task. Comparable data from a patient with bilateral frontal lobe damage and from normal older adults born about the same year as H.M. indicated that H.M.'s comprehension deficits were specific to his lesion, and not due to cohort effects or to brain damage *per se*. Further strengthening the case against stages-of-processing theories, 17 patients with unilateral left-sided surgical resection of the amygdala and anterior hippocampus exhibited similar comprehension deficits on the same task (Zaidel, Zaidel, Oxbury, & Oxbury, 1995).

## NEW THEORETICAL PREDICTIONS REGARDING H.M.'S LANGUAGE PRODUCTION

Although all distributed-memory theories share characteristics that distinguish them from stages-of-processing theories, distributed-memory theories vary greatly in specific mechanisms. They differ in the number and types of activation states that a node can assume, in the mechanisms for node activation, in the types of nodes postulated and how they interconnect, and in the way that inhibitory connections are deployed. Distributed-memory theories also vary enormously in scope and detail, and we focus on MacKay's (1990) Node Structure theory (NST) because it addresses all of the issues that are important for making detailed predictions regarding H.M.'s language abilities: it refers to the hippocampal system and its relation to connection formation processes for language production at phonological and semantic levels, and it refers to relations between language comprehension and production, including mechanisms for controlling timing and sequencing in language production and comprehension. We will examine how NST's theoretical mechanisms predict specific deficits in H.M.'s language production. However, we omit extraneous details wherever possible, together with the extensive data that originally motivated these mechanisms (but see MacKay, 1987; MacKay & Abrams, 1996; and MacKay & Burke, 1990).

Under NST, the same network underlies language production and memory retrieval involving verbal information, and three memory-related processes occur many times a day during everyday language comprehension and production: activation processes; the strengthening of existing or already established connections; and the formation of new connections between nodes. We first discuss activation processes and the structure of the network for verbal memory and language production in NST, then mechanisms for strengthening existing connections and forming new ones, and finally, NST predictions concerning H.M.'s language production.

### *Activation Processes and the Structure of Established Connections*

Many aspects of language production involve activation of nodes with connections that have been formed and used since childhood, e.g., producing words such as *frisbee,* familiar phrases such as *good morning,* and frequently used propositions such as *Two plus two equals four.* Under NST, nodes for producing such familiar units are organized hierarchically in the manner illustrated in Figure 2, which represents some of the top-down connections for producing the word *frisbee* (modified from Burke, MacKay, Worthley, & Wade, 1991). Declarative memories related to frisbees, i.e., ones that ''can be declared'' or produced as speech (Squire, 1987, p. 152), consist of a set of propositions associated with the lexical node for *frisbee* in the semantic memory system (see Figure 2 for examples). Phonological memory for producing *frisbee* consists of the hierarchy of phonological nodes headed by the lexical node labeled *frisbee*(noun) (see Figure 2). Muscle movement memory for articulating the sequence of tongue and larynx movements in the word *frisbee* consists of hierarchies of muscle movement nodes headed by the phonological nodes for *frisbee* (Figure 2 shows only a single muscle movement node for contracting the temporalis muscle of the larynx for producing a devoiced speech sound).

Activating a node in NST hierarchies resembling Figure 2 has several consequences: One is that all directly connected nodes become primed or readied for activation. However, priming by itself is insufficient to cause activation, which always requires a sequence node, a non-specific activating mechanism (not shown in Figure 2) that when applied, activates the most primed node in a sequential domain (shown in brackets in Figure 2). For example, a single sequence node is responsible for activating whatever node is most primed in the sequential domain (noun), which consists of all of the lexical nodes for nouns in the speaker's lexicon. The main function of sequence nodes is to ensure that node activation proceeds in proper sequence and at proper rate, as required for normal language production (see MacKay, 1987, pp. 39–61).

A second consequence of activating a node is that its connections with other already established or ''committed'' nodes become strengthened, a process known as engrainment learning. Because connection strength determines how much priming a connection will deliver, and because sequence nodes only activate the most primed node in a domain at any given time, engrainment learning has a wide variety of effects: Engrainment learning is the means whereby rehearsal or repeated node activation facilitates recall; Cumulative effects of engrainment learning over the course of a lifetime also determine frequency effects at all levels of memory and language, e.g., shaping the nature of speech errors at phonological and lexical levels in language production (see MacKay, 1987, p. 89), and determining whether a verbal memory can be retrieved or remains ''on the tip-of-the-tongue'' (see, e.g., Burke et al., 1991). Such effects of engrainment learning make it important to know the relative connection strength of units at different levels in the language-memory system, and MacKay (1982) showed that for hierarchies resembling Figure 2, connection strength in normal adults speaking their native language is strong and close to asymptote for muscle movement nodes, and tends to decrease with level in the hierarchy for phonological, lexical, phrase and proposition nodes,

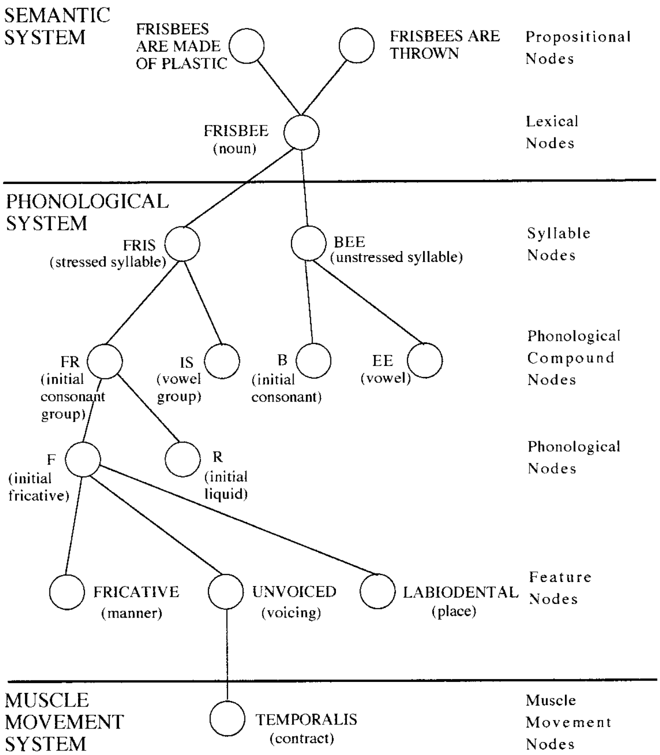


**FIG. 2.** Top down connections for producing selected aspects of the word *frisbee* in NST (modified from Burke, et al., 1991). Memory storage is distributed across connections between large numbers of nodes, and word retrieval is inseparable from word production. Binding nodes for forming new connections are not shown.

with connection strength approaching zero for rarely used phrases and propositions. However, there are exceptions to this general ''strength-level correlation'' because propositions can vary enormously in their frequency of use over the course of a lifetime: Connection strength can approach asymptote for declarative memory propositions representing familiar facts such as ''Two plus two equals four'', but can be extremely weak and fragile or subject to decay for declarative memory propositions representing unique and unrehearsed events that occurred at a particular time and place, e.g., ''*Cloud* was the third word in the just presented experimental list''.

### *Forming New Connections and Committing New Nodes*

Everyday sentences often communicate new or never previously expressed ideas at phrase and proposition levels, and representing these new ideas during language comprehension and production requires new nodes and new cortical connections within the semantic system. For example, to retrieve or produce the never previously encountered noun phrase *binding node,* a chunk node representing the conjunction of *binding* and *node* must be formed in two stages: First, new bottom-up connections must link existing lexical nodes for *binding* and *node* to the chunk node, a step essential for comprehension when the chunk is subsequently linked to propositions. In step two, new connections are formed top-down from the chunk node to *binding* and *node,* enabling retrieval of the chunk during explicit recall and language production, including everyday conversation (see MacKay & Burke, 1990). As in this example, cortical nodes for comprehending and producing units are identical at semantic and phonological levels in NST, unlike other theories (see MacKay, 1987, pp. 14–194).

Special mechanisms within the hippocampal system known as binding nodes are normally engaged to help form both bottom-up and top-down connections (see MacKay, 1990). Binding nodes enable the rapid formation of new connections, and different types of binding nodes specialize in conjoining different classes of units. For example, to initially learn the phrase *binding node,* a specific type of semantic binding node is engaged for linking a participle (*binding*) with a noun (*node*) to represent a noun phrase (*binding node*). Similarly, to initially learn the participle *binding,* a specific type of morphological binding node is engaged for conjoining a verb (*bind*) and a verb suffix (*-ing*). Likewise, to initially learn the phonological form, *bind,* a specific type of phonological binding node is engaged for conjoining an onset or initial consonant group (*b-*) and a rime or vowel group (*-ind*). It is therefore possible in principle to selectively destroy, say, phonological binding nodes in NST without destroying semantic binding nodes, so that new connections can be formed for representing novel propositions, but not for representing never previously encountered phonological forms, e.g., words in a foreign language (see Vallar & Baddeley, 1984, for such a case).

Under NST, thousands of binding nodes play a role in the normal comprehension, production and acquisition of language (at all ages), and different binding nodes can overlap in what nodes they conjoin, e.g., one binds any adjective to any noun, and another binds any adjective to any adverbial suffix (e.g., *-ly*).[1] There also exist a surplus of binding nodes for binding whole domains of new or uncommitted nodes, so that any node in the semantic system can potentially connect with any other semantic system node with the help of binding nodes. However, binding nodes are assumed to come prewired at birth as part of the innate basis for language acquisition, so that destroyed or damaged binding nodes cannot be replaced by new ones (see MacKay, 1990).

*Relations between Binding and Engrainment Learning*

Unlike other theories where binding mechanisms only establish fleeting or temporary traces that never become durable or permanent (see Cohen & Eichenbaum, 1993, pp. 286–87), NST postulates close relations between binding and engrainment learning that enable establishment of permanent connections. Node activation in NST is normally a brief and self-terminating process that increases by a trivial amount the strength of connections to committed nodes. However, binding nodes cause two or more activated nodes to prolong their activation over an extended period, thereby increasing connection strength to a nontrivial degree, especially for the weak connections to new or uncommitted nodes. Assume, for example, that a noun phrase binding node prolongs the activation of semantic system nodes representing the concepts *binding* and *node.* Prolonged activation of these nodes essentially speeds up the engrainment learning process, causing a rapid boost in connection strength, especially for the extremely weak connections that both *binding* and *node* send to chunk nodes. This rapid boost in connection strength, together with the prolonged priming accumulated conjointly from both *binding* and *node,* enables one of these previously uncommitted chunk nodes to amass sufficient priming to become activated as the most primed node in the noun phrase domain. Activation further strengthens these newly formed and extremely fragile connections so that the chunk node temporarily represents the conjunction of *binding* and *node,* but not permanently: Unless the chunk node is activated again within a critical period, say several days, connection strength will decay, and the chunk node will revert to uncommitted status, i.e., it can only be activated via additional hippocampal input. For example, if the newly bound

[1] See MacKay (1990, 1992) for a discussion of conditions that trigger binding nodes and constrain what domains of committed nodes can be directly conjoined.

concept *binding node* is not activated for several days, the strength of its bindings will decay to zero, and its chunk node will no longer represent the concept *binding node.* This has a negative consequence (the noun phrase *binding node* will no longer be retrievable without a new binding process) and a positive consequence: the chunk node can potentially represent some other novel conceptual conjunction, say, *fluid memory,* because each uncommitted node receives hundreds of redundant and initially nonfunctional connections. However, if the newly bound concept *binding node* is used repeatedly during the critical period since last activation, the engrainment learning mechanism will eventually increase the strength of its bindings to permanent or ‘‘commitment’’ status, so that its chunk node can *only* represent the concept *binding node* and will be activated automatically without hippocampal input during normal language comprehension and production.

To summarize, hippocampal input initially helps to form new connections by enhancing the engrainment learning process, and further engrainment learning serves to make these connections permanent. Moreover, engrainment learning can also form new connections initially, albeit slowly and inefficiently without supplementary hippocampal input: Because hippocampal binding is only an accelerated form of engrainment learning, sufficient rehearsal or repeated activation will eventually commit new connections at any level in the network. For example, consider the phonological connections from the syllables *fris* and *bee* to the lexical node for *frisbee* in Figure 2. When a normal child first encounters the word *frisbee,* input from hippocampal binding nodes helps to form the new connections between *frisbee* and its syllables *fris* and *bee* without extensive rehearsal. However, hundreds of repetitions of *fris-bee,* each during the critical period, would also suffice to form these new connections via engrainment learning without hippocampal binding input. Subsequent uses of *frisbee* without hippocampal binding input will then commit this lexical node, and the strength of its established connections will gradually increase for each use over the course of a lifetime.

### *Applications of NST to H.M.’s Language Production*

Under NST, H.M.’s lesion will not impair his ability to produce *familiar* syllables, words, phrases, and propositions because activation via already functional connections does not require hippocampal binding input. For example, H.M. will be able to produce the syllable *bee* in words such as *be* and *bee* and the syllable *fris* in words such as *frizzy* because he learned these words prior to his operation. However, H.M.’s lesion has irreversibly destroyed some (but perhaps not all) of the binding nodes required to efficiently establish new connections for representing novel words and ideas in language comprehension and production. Moreover, because comprehension and production engage identical binding nodes, H.M.’s comprehension deficits (see MacKay et al., 1997) predict corresponding production deficits under NST. In particular, H.M.’s language production should be especially slow and inefficient when new semantic-level connections must be formed (see MacKay, 1990). For example, it is unlikely that H.M. has formed the connections for conjoining the syllables *fris* and *bee* in *frisbee* (see Figure 2) because this word entered the English language after H.M.’s 1953 operation. Nonetheless, H.M. will be able to form weak or fragile connections for semantic-level production of *frisbee* by sequentially repeating the syllables *fris* and *bee* a large number of times.[2] With even more extensive repetition, H.M. may likewise be able to form propositional connections within the semantic system for using *frisbee* appropriately in a sentence.

[2] Freed et al. (1987) present data that are relevant to the hypothesis that H.M. can form weak or fragile new connections, but requires extensive repetition for these connections to achieve normal levels of strength. For H.M., Freed et al. had to multiply the time available for rehearsal by a factor of 20 in order to equate initial performance of H.M. and memory-normal controls in a yes-no recognition memory task.

However, H.M. must first form the lower level connections in order to form the higher level connections via engrainment learning. To illustrate this point, consider H.M.'s problem with Drachman and Arbit's (1966) ''extended span'' task. The first step in Drachman and Arbit's procedure is to determine the longest sequence (n) of digits that participants can immediately recall. Then another digit is added to the sequence, which is presented repeatedly until the subject can correctly recall this n + 1 sequence. Then another digit is added to the n + 1 sequence, which is repeated up to 25 times, to determine the longest possible ''extended span'' following 25 repetitions. This repetition procedure enables memory-normal controls to extend their span up to 20 digits, because with input from hippocampal binding nodes, they can quickly form new connections for chunking the incoming digits. Repetition then increases the linkage strength of these initially weak and fragile new connections so that an n + 1 string can be recalled, and an even longer list can be presented. However, the extended span procedure had no effect for H.M.: Even after 25 repetitions, H.M. was unable to recall a string of 7 digits, one digit longer than his normal span. The reason is that higher level chunk nodes must first be formed in order to benefit from list repetition on subsequent trials. However, with ungrouped and rapidly presented digits, H.M. is able neither to form chunks using hippocampal binding nodes, nor to repeatedly rehearse, e.g., digit pairs, so as to form the new connections to chunk nodes that can later benefit from list repetition. A similar explanation applies to H.M.'s failure to benefit from unnoticed repetitions in the Hebb task (see Corsi, 1972). Nonetheless, with long pauses between groups of digits, and instructions to rehearse each group during the pause, NST predicts that H.M. should benefit from repetition in both the extended span and Hebb tasks.

In addition, NST predicts two types of spontaneous repetition in H.M.'s speech production, one type reflecting H.M.'s difficulty in forming the new connections for ''tagging'' what he has said as ''already described,'' and the other type reflecting a deliberate tendency to use rehearsal or engrainment learning to form new connections. This second type of repetition explains how H.M. has learned to recognize definitions of a small number of high frequency words that entered English after his operation (Gabrieli et al., 1988), and to remember some frequently encountered post-operative information such as President Kennedy's death (albeit inconsistently from one day to the next; Milner et al., 1968), and even to remember frequently repeated aspects of experimental procedure over several days (Milner et al., 1968).

NST also predicts that H.M. will generate sentences that are less comprehensible, less grammatical, and less coherent, relative to memory-normal controls, because his binding deficit will reduce his ability to form the new semantic-level connections required to represent propositions that are appropriate, coherent, grammatical, and readily understood. In order to minimize how many new connections he must form during language production, H.M. will also use clichés or familiar phrases more often than memory-normal controls.

## STRUCTURE OF THE PRESENT PAPER

The present research has two main goals: to test the prevailing stages-of-processing view of H.M.'s language production, and to test the specific and contrasting predictions of NST. However, to address these goals we had to circumvent what Corkin (1984, p 254) described as H.M.'s ''premature aging,'' a late-onset deterioration in ''general cognitive capacities'' that is independent of H.M.'s hippocampal system lesion. That is, tests conducted in the early 1980's seemed to suggest a dramatic decline in H.M.'s cognitive abilities, including most notably, his language production abilities on tests of semantic and symbolic verbal fluency and on the reporter's test of language production. These observations suggested that examining H.M.'s current language production abilities could not provide a fair test of stages-of-processing theories. Rather, data collected prior to 1984 were needed to obviate H.M.'s general cognitive decline, and to test for the specific production deficits predicted under NST.

The present research therefore focused on H.M.'s language production in two tasks performed during 1970–1973.[3] One was Corkin's (1973) ambiguity description task, where H.M. described the two meanings of ambiguous sentences to an experimenter. As a fundamentally semantic task that neither explicitly tested memory nor involved delayed recall (tasks where H.M. has known deficits; see, e.g., Keane et al., 1987), this ambiguity description paradigm seemed appropriate for testing NST, which predicts deficits in H.M. at semantic levels where new connections are required, but not at phonological levels for producing familiar words. Study 1 analyzed the language output of H.M. and memory-normal controls in this task using ''local measures,'' e.g., word counts. Study 2 examined global measures of communicative ability in this same task by having naive judges rate the ambiguity descriptions of H.M. and memory-normal controls for comprehensibility, grammaticality, and coherence (tangential or off-topic speech). Study 3 used rating procedures similar to Study 2 to compare the conversational speech of memory-normal controls and H.M. in the unpublished transcript of Marslen-Wilson (1970). In this 1970 task, H.M. described events that occurred well before age 12-16, thereby engaging memories and retrieval processes that are believed to be intact and normal in H.M. (see, e.g., Sagar et al., 1988).

## STUDY 1: H.M.'S COMMUNICATIVE ABILITIES IN CORKIN (1973)

Study 1 examined the communicative abilities of H.M. and memory-normal controls performing Corkin's (1973) ambiguity description task. In a tape recorded session, Corkin had H.M. read 32 ambiguous sentences one at a time with instructions to briefly describe the two meanings of each sentence in any order. Study 1 replicated these procedures as closely as possible for memory-normal controls matched with H.M. in age, education, and intelligence at about the time of test. We then developed verbatim transcripts of the controls' output for comparison with H.M. in Corkin's (1973) transcript.

To check for possible differences in motivation between H.M. and controls, Study 1 examined how many words participants used in describing the two meanings of the sentences. However, the main theoretically motivated measures in Study 1 were communicative effectiveness of the descriptions (defined below), and repetition of familiar phrases and propositions. Stages-of-processing theories predicted equivalent communicative effectiveness and repetition for H.M. and memory-normal controls. NST predicted greater repetition of familiar phrases for H.M. than for memory-normal controls because of H.M.'s greater reliance on connections formed before his operation. NST also predicted greater communicative effectiveness for memory-normal controls than for H.M. because of the many new connections that are required to represent and describe the two meanings of ambiguous sentences. By way of illustration, Figure 3 indicates two of the new connections required in NST to represent both meanings of the syntactic ambiguity, ''They talked about the problem with the mathematician'' (from Corkin, 1973). That is, the listener must connect the node for the concept ''with the mathematician'' to ''talked'' in order to represent the meaning ''talked with the mathematician'', and to ''problem'' in order to represent the meaning ''problem with the mathematician''.

Figure 4 illustrates the sequential process underlying formation of some of the new connections for representing first one and then the other meaning of the lexical ambiguity, ''The soldier put the gasoline in the tank'' (also from Corkin, 1973). We assume that the lexical node for ''military tank'' (labeled TANK 1 in Figure 4) and the lexical node for ''container tank'' (labeled TANK 2 in Figure 4) have been formed during childhood, and that pre-

[3] After completing the present research we learned that H.M.'s alleged 1984 decline does not appear to be a genuine change in cognitive abilities (Corkin, January, 1997, personal communication).

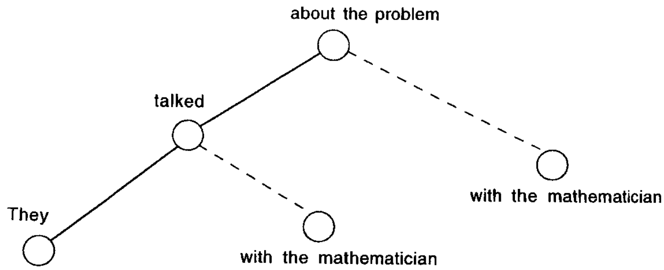


**FIG. 3.** New connections (shown with broken lines) required in NST to represent the meanings, ‘‘talked with the mathematician’’, and ‘‘problem with the mathematician’’ for the surface structure ambiguity in the sentence, ‘‘They talked about the problem with the mathematician.’’ To simplify the illustration, the single concept, ‘‘with the mathematician,’’ is represented via two nodes rather than one, and only the node for ‘‘problem’’ is shown: Connections representing the internal structure of the phrase ‘‘about the problem’’ have been omitted.

senting the word *tank* automatically primes both of these lexical nodes to varying degrees depending on the strength of their bottom-up connections. However, these lexical nodes also receive priming from a large number of ‘‘contextual sources’’ (e.g., the word *soldier* in this sentence; see MacKay & Bever, 1966, for other contextual sources), and these sources of contextual priming can influence whether ‘‘military tank’’ or ‘‘container tank’’ receives most priming and becomes activated for a given sentence and for a given listener at a given time. However, for didactic purposes, we simply assume that ‘‘military tank’’ is the more dominant meaning when the hypothetical listener in Figure 4 hears the sentence, ‘‘The soldier put the gasoline in the tank’’. Consequently, TANK 1 is activated, and the

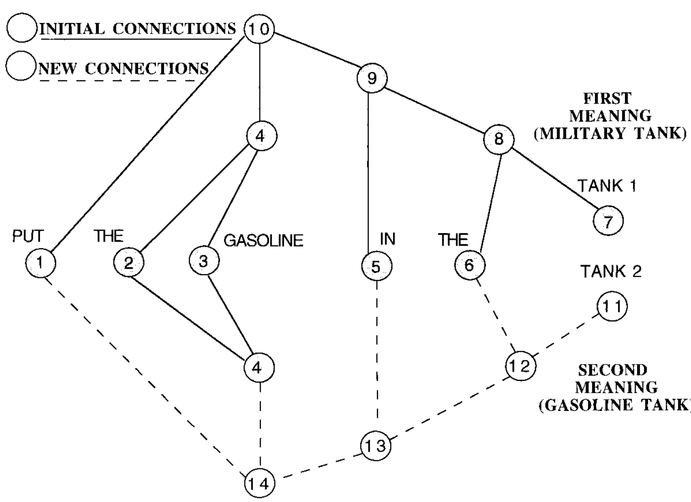


**FIG. 4.** Connections for representing the two meanings of the lexical ambiguity, ‘‘The soldier put the gasoline in the tank.’’ Filled circles and solid lines represent nodes and connections for representing the first meaning (by assumption, military vehicle). Unfilled circles and broken lines represent new nodes and connections for representing the second meaning (gasoline tank). The numbers within nodes indicate order of activation, which determines the order of new connection formation. To simplify the illustration, the single concept, ‘‘the gasoline,’’ is represented via two nodes rather than one.

listener forms a set of new connections for representing the soldier's act of injecting gasoline into a military vehicle. Consequently, even though H.M. would have formed the lexical node for TANK 1 long before his operation, he would have difficulty representing the ''military vehicle'' meaning at the sentential level because of the new connections that are required to link this lexical node to its novel context in this particular sentence. H.M. would also have difficulty representing the second meaning of this sentence because in order to activate TANK 2, a new connection must be formed to inhibit the most primed or dominant meaning, TANK 1, and further new connections must be formed to link TANK 2 to its novel context in this sentence in order to represent the act of pouring gasoline into a container for liquids. As can be seen in Figure 4, which shows nodes and new connections for representing the first meaning (TANK 1) as shaded with solid connections, and nodes and new connections for representing the second meaning (TANK 2) as unshaded with broken connections, many new connections must be formed to represent ''military vehicle'' as the first perceived interpretation, and many additional new connections must be formed to represent ''container'' as the second perceived interpretation, and under NST, forming both sets of new connections will be especially difficult for H.M. due to his binding deficit or reduced ability to form new connections.

The task of perceiving the two meanings of ambiguous sentences is particularly sensitive to deficits in new connection formation for another reason that can be discerned in Figures 3 and 4: Representing both meanings of ambiguous sentences always requires formation of two sets of new connections from one and the same node or set of nodes. This double connection process involving the same node(s) is known to be difficult for normal older adults (MacKay, Miller & Schuster, 1994; MacKay & Miller, 1996b; and MacKay et al., 1997), and for young adults under extreme time pressure (see, e.g., Abrams, Dyer, & MacKay, 1996), and can be expected to be especially difficult for an individual such as H.M. with a reduced ability to form new connections.

## *Method*

*Participants.* Participants for Studies 1-3 included H.M. and seven memory-normal controls. Recent MRI data (Corkin, Amaral, González, Johnson, & Hyman, 1997) indicate that H.M. has cerebellar damage due to his large and long term doses of dilantin and other drugs for controlling epilepsy, and that his bilaterally symmetrical surgical lesion includes virtually all of the amygdaloid complex, some entorhinal cortex, and the anterior rostrocaudal extent of the intraventricular portion of the hippocampal formation (dentate gyrus, hippocampus, and subicular complex). Spared are the temporal stem, parahippocampal cortex, the collateral sulcus, including portions of the ventral perirhinal cortex, and the caudal 2 cm of the hippocampal body, although the current functional status of this spared 2 cm is not known. Also spared is virtually the entire neocortex because of the suborbital route of H.M.'s lesion (Scoville & Milner, 1957).

Controls for Studies 1-3 (5 female, 2 male) were native English speakers, between 45 and 50 years of age, who were similar to H.M. in 1973 age,[4] highest educational level, and verbal IQ (Corkin, 1984). Table 1 shows these characteristics, together with performance IQ, which was higher for H.M. than for controls (126 versus 109.3). Controls were paid $10/hour for participating, and were recruited through their places of employment in clerical or physical plant positions in a college community. None held a college degree, although some reported having taken one or more college courses. Controls 1-3 were randomly selected to receive Corkin's procedure.

*Procedures and materials.* In session one, all controls completed the WAIS-R, and in

[4] When Corkin tested him in 1973, H.M. was 47, but his closest IQ test was conducted in 1977 when H.M. was 51. Because H.M.'s 1977 IQ test (the Wechsler Bellevue, Form 1) is currently out of print, we tested controls on the (1983) Wechsler Adult Intelligence Scale R (WAIS-R).

TABLE 1

Age (years), Verbal IQ, Performance IQ, and Educational Level (Highest Degree) for Control Participants and H.M. at Time of Test

| Participants | Verbal IQ | Performance IQ | Highest degree | Age at time of study |
|---|---|---|---|---|
| H.M. | 107 | 126 | high school | 47 (in 1973) |
| | | | | 44 (in 1970) |
| Controls (Mean) | 107.5 | 109.3 | high school | 47.5 (in 1996) |
| Control 1 | 104 | 111 | high school | 49 |
| Control 2 | 114 | 101 | high school | 49 |
| Control 3 | 112 | 122 | high school | 47 |
| Control 4 | 104 | 96 | high school | 50 |
| Control 5 | 116 | 114 | high school | 47 |
| Control 6 | 112 | 120 | high school | 46 |
| Control 7 | 93 | 99 | high school | 45 |

session two, several days later, Controls 1-3 were tested in the Corkin procedure. Materials were 32 ambiguous sentences used by Corkin (1973) and originally developed and published in MacKay and Bever (1967). The sentences were short (mean length 7.7 words; range 7-9 words), and syntactically simple: None contained complex embedded or subordinate clauses. The two meanings for each sentence were about equal in bias, the probability across a large sample of control participants that one meaning or the other would be perceived first (see MacKay & Bever, 1967). The sentences were printed in large font on sheets of paper, and were presented to each participant one at a time, with instructions to find the two meanings of each sentence, and briefly describe both meanings in any order. Like Corkin (1973), we first presented example ambiguous sentences to illustrate the concept of ambiguity, but controls received fewer examples than did H.M. We presented the test sentences in the same order as Corkin (1973): lexically ambiguous sentences, e.g., ‘‘The soldiers took the port at night’’, followed by surface structure ambiguities, e.g., ‘‘They talked about the problem with the mathematician’’, followed by deep structure ambiguities, e.g., ‘‘The mayor asked the police to stop drinking’’ (see MacKay & Bever, 1967, for definitions and additional examples of these three types of ambiguity). Also like Corkin (1973), we tape recorded session two, and developed detailed verbatim transcripts that included errors, pauses, word repetitions, filled pauses (‘‘ers’’ and ‘‘uhmms’’), for experimenter and participants alike.

In preparing to administer these procedures, the experimenter (R.S.) familiarized herself with five types of interjections that Corkin repeatedly produced when working with H.M. (see Tables 2a,b,c for examples), and produced similar interjections wherever appropriate when testing controls. *Assistance interjections* occurred when Corkin found it necessary to give summary feedback, e.g., ‘‘So you’re saying that he like (sic) his job in other words’’ (see Table 2a), or to give information relevant to one of the meanings, or to give one or both meanings outright, e.g., ‘‘Over a week ago can mean more than one week ago.’’ *Elaboration interjections* occurred when Corkin asked a question or probed for further information, e.g., ‘‘How do we know that?’’; ‘‘What do you mean by office?’’; ‘‘Now, there is another meaning in that sentence. Can you tell me what it is?’’ (see Table 2a). *Reminder interjections* occurred when Corkin reminded H.M. of the instructions or advised him to stay on task, e.g., ‘‘. . . just stick right with that very sentence; I don’t want you to go beyond that sentence.’’ *Clarification* interjections occurred when Corkin requested that H.M. clarify his intended meaning, e.g., ‘‘I don’t

TABLE 2

2a: The complete transcripts for H.M. and controls describing the ambiguity in, The marine captain liked his new position. Underlined aspects of H.M.'s transcript are discussed in the text. Brackets, e.g., [C1] and [H.M.] indicate response excerpts used in Study 2.

Control 1 Response

[C1]: Either, um, job-related, or the way he was laying.

Control 2 Response

[C2]: Okay. That too could be either a physical way of doing things or a professional . . . professional post that he is now holding.

Control 3 Response

[C3]: He was pleased with his promotion or his new position in life, or it could mean his . . . position—sitting, standing.

H.M. Response (from Corkin, 1973)

[H.M.]: The first thing I thought of was a marine captain he liked the new position on a boat that he was in charge of, the size and kind it was and that he was just made a marine captain and that's why he liked the position too, because he was above them and of all, most of all. . . .
S.C.: So you're saying that he like (sic) his job in other words.
H.M.: He liked his job.
S.C.: Okay. Now, there is another meaning in that sentence. Can you tell me what it is?
H.M.: I just gave you two.
S.C.: Those are both really the same. Because they were both related to his job. There is another meaning.
H.M.: Well, cause he was on a new boat, you might say a new boat, he was made captain of a new liner or whatever it is and it's different than what he had before. He might have had a . . . a . . . a. . . .
S.C.: You mean his job was different.
H.M.: Yes, he might, he has people. . . .
S.C.: That's the same meaning that you told me. There's another meaning that's suggested by those same words, in that same order, something. . . .
H.M.: Well, you see, I thought of marine captain in a new position, was one, was transporting goods, he was a marine captain of a boat there and then marine captain he liked the new position because of being, being a passenger line, I'd guess you'd call it, because of the people that would. . . .
S.C.: All right, I'm going to tell you what the other meaning is. One meaning, that one that you have, means that he likes his new job. The other meaning is that he likes his new physical position. In other words, he may have been standing up on watch for a great number of hours and then he gets to sit down and he likes that new position of being able to sit down. The position of his body.
H.M.: Oh.
S.C.: Okay? Do you see how those are really rather different meanings?
H.M.: They're different.
S.C.: One has to do with his job and the other is if he is sitting, standing or whatever.
H.M.: The position he's in.
S.C.: The position of his body. OK, you see? Do you understand how the very same words can mean two rather different things, two different interpretations depending on how you read it. OK. (next trial).

2b: The complete transcripts for H.M. and controls describing the ambiguity in, He told me to go without any hesitation. Brackets, e.g., [C2] and [H.M.] indicate response excerpts used in Study 2.

Control 1 Response

[C1]: He told me to go without any hesitation. Hesitation could be on my part or on his part.

TABLE 2—*Continued*

Control 2 Response

[C2]: He told me to go without any hesitation. He told me to go without any hesitation. He either wants me to go and not feel anything bad about it or he has no problem telling me to go.

Control 3 Response

[C3]: He told me to go without any hesitation. He told me to go without even bothering to . . . he just . . . I can't say it. He told me to go without any hesitation—he didn't . . . think twice about telling me to go. He told me to go without any hesitation—he told me to hurry up and go and stuff. Don't dilly-dally.

H.M. Response (from Corkin, 1973)

[H.M.]: Well I thought of a person being told something the straight-forward out style that the other person was telling him without stopping him or stopping in it or freely and uh, then I also think of a person being told something by a person, uh, straight-forwardly, like the other, he told him right out, straight out, quick, ah, not quicker, but easy. The other one maybe just didn't know the person personally that he was talking to, but told him without stuttering or stammering or in any way, just hear about it, whatever it was. Two way.

S.C.: That's one. Well, I think I've just one. I'm not really clear how you have two different meanings there.

H.M.: Well, one meaning, I think of, he told without any hesitation. He spoke right out quick.

S.C.: OK. Right. That's right. That's one. He told it without hesitation.

H.M.: Yeh, he spoke out straight and quick. And now

S.C.: Right. Good. What's the second one?

H.M.: The second meaning would be that the person was told something about whatever it was around straight-forwardly.

S.C.: That's the same meaning.

H.M.: The same meaning?

S.C.: Uhmm, now, there's a completely different meaning that you can get out of these same, those very words. That sentence there has a different meaning.

H.M.: Clean in the morning. First, he told him without, straight-forwardly and there was one that the person was spoke direct to him or me or was to that one person, one speaking to another, I say.

S.C.: Right. Now, what's the other meaning?

H.M.: Uh, the way it was spoken is what I think of.

S.C.: That's the same one. That's still the same meaning you gave me. That he told it without hesitation.

H.M.: No, I said he told me or . . .

S.C.: We're just going to stick to the words there. That's right. He told

H.M.: I am.

S.C.: Right.

H.M.: One person

S.C.: Right.

H.M.: without hesitation

S.C.: That's right. That's the way he told it.

H.M.: He told me without any hesitation.

S.C.: Uhmmm, mmm.

H.M.: To go without any hesitation.

S.C.: Try reading the sentence out loud.

H.M.: ''He told me to go without any hesitation.'' Uhmmm. Well, that person was told to go, without hesitation, that means he didn't stutter or slow up on it when he was telling him to go.

S.C.: Uhmmm.

H.M.: And, uh, get away from he, each other.

S.C.: uhmmm.

H.M.: Do it quickly without hesitation.

S.C.: All right, now, I think you've got the second meaning there. I just want you to sort of rephrase it a little so that I can be sure.

H.M.: Well, one would be to leave without hesitation.

TABLE 2—*Continued*

S.C.: Right. That's right, that's the second meaning. The first one was to tell it without hesitation and the second one was to get out of there without hesitating. Right. Good.

2c: The complete transcripts for H.M. and controls describing the ambiguity in, <u>Mary and I approved of his cooking</u>. Brackets, e.g., [C3] and [H.M.] indicate response excerpts used in Study 2.

Control 1 Response

[C1]: Hmm. Um I don't know. Mary and I were happy with his cooking . . . but I can't, do I see another . . . meaning? Oh, that you allowed him to cook.
R.S.: Okay, so what do you mean by cooking in the two different meanings?
C1: Okay, Mary and I approved of his cooking—that, that, we liked the way his cooking tasted.
R.S.: Okay, so the actual food is one meaning of cooking.
C1: Or else you approved of his cooking—so you were going to allow him to try to cook.

Control 2 Response

C2: Hmmm . . . approved of his cooking. Agree on his cooking. Huh. . . .
R.S.: Okay, so Mary and I approved of his. . . .
[C2]: Agreed of his—on his act of doing the cooking, or then there's the actual cooking itself.

Control 3 Response

[C3]: Okay. Mary and I approved of his cooking. Either they liked what he is cooking or they approve of the fact that he's actually cooking.

H. M. Response (from Corkin, 1973)

H.M.: ''Mary and I approved of his cooking.'' <u>Well</u>, Mary approved of his cooking. . . .
S.C.: Well, it's Mary and I.
H.M.: <u>Well</u>, for two things. I said Mary and I approved of his cooking.
S.C.: Yeh, but
H.M.: and
S.C.: Let me just say something now. You're getting off on the wrong track because you're not using all of the words in the sentence. You have to use all of the words for each meaning.
H.M.: ''Mary and I approved of his cooking.'' that it'd be. . . .
S.C.: Those words, ''Mary and I approved of his cooking,'' have two different meanings.
H.M.: <u>Well</u>, one, they, uh, Mary and I could be a comma too, approved of, that means both Mary and I liked his cooking and
S.C.: Now, what does that mean?
H.M.: <u>Well</u>, liked it or enjoyed it—is one way I'd say of liking it.
S.C.: What was it they enjoyed?
H.M.: His cooking.
S.C.: What do you mean?
H.M.: What he, uh, the things and the way he cooked things. So it'd be his cooking 'cause he cooked them a certain way that he cooks them.
S.C.: Uhmmm.
H.M.: and they enjoyed the way that he cooked them.
S.C.: OK.
H.M.: And <u>I think of</u> the other
S.C.: In other words, the finished product was what they
H.M.: Yeh, they enjoyed his cooking.
S.C.: All thought that it was (gesture), the hamburgers or something like that.
H.M.: Yeh. And also, <u>I think of</u> they, ''Mary and I approved of his cooking'' being also that they just liking, wished that they could cook like he did.
S.C.: Is that what that says?
H.M.: It says they approved of it. The interpretation, they approved of his cooking, they liked his cooking.

TABLE 2—*Continued*

S.C.: That's the same as the first meaning.
[H.M.]: Yeh, in a way. One is, they approved of it means that the two like it. The other is to do it, to like to do it his way. That's what interpretation I was getting and Mary and I approved of his cooking the way he cooked it and and
S.C.: Give me an example.
H.M.: Well, they approved of his cooking, they liked his cooking.
S.C.: All right, use different words.
H.M.: Well, let's see.
S.C.: Give me, illustrate it.
H.M.: Well, they lik, (sic); they, uh, liked, my other sentence is they liked his cooking but so well, they wished it
S.C.: Now, what does that mean?
H.M.: They liked it, they enjoyed it in a way.
S.C.: What was it that they enjoyed?
H.M.: His cooking.
S.C.: Now, what does that mean? You've got to use different words because if you just stick to these words, by definition, it has two meanings. That's what the task is, to figure out the two meanings so that if you only
H.M.: They liked it, the way he cooked it, himself, liked his cooking, his cooking. They approved of it and approved can be liked. Mary and I liked his cooking.
S.C.: What about it?
H.M.: They liked it. That's approved.
S.C.: Right.
H.M.: And it was his.
S.C.: But you see, you've got to . . . use different words. (lengthy interruption while Mrs. M. shuts a window and H.M. puts on his shoe). Try this once more and I want you to try not to use those words in explaining it to me. Try to explain it to me using different words because these words, this sentence here, those words together have two different meanings so if you stick to those words I'm still not going to know which meaning you mean. Do you understand my problem?
H.M.: Yeh, well, ah.
S.C.: So try and use different words.
H.M.: Say, can I use Mary and I?
S.C.: Yes.
H.M.: Uh. Mary and I liked his way of preparing food.
S.C.: Fine, that's one meaning.
H.M.: And
S.C.: In other words, we thought he was a good cook.
H.M.: We thought he was a good cook.
S.C.: OK.
H.M.: And good cooking, approved of his cooking, approved, I think of as Mary and I approved of his cooking, would be, ah, they liked his cooking for us and enjoyed his cooking. Mary and I enjoyed his cooking.
S.C.: Now, that doesn't say enjoyed. It says approved.
H.M.: Well
S.C.: We don't want to change
H.M.: Approved.
S.C.: the meaning completely.
H.M.: Can't think of the word for uh approved, but they, the definition of approved could be they liked it as well.
S.C.: Now, what was it that they liked?
H.M.: They liked his cooking.
S.C.: What does that mean? Is this different from your first meaning? The first meaning is that they thought he was a good cook . . .
H.M.: They thought he was a good cook.
S.C.: that the things that he turned out and served to them were good.
H.M.: And, uh, Mary and I approved of his cooking could mean that they enjoyed eating his cooking.
S.C.: OK. Now, there's another meaning that that sentence has and it has nothing, it doesn't say anything about the quality of his, the finished product. What it says is they thought it was a good idea that he cooked.
H.M.: Well, they thought it was a good idea
S.C.: Do you understand? That they approved

TABLE 2—*Continued*

H.M.: (Echoing) that they approved, they agreed, they liked it
S.C.: they approved of the fact that he was doing this task and it, this doesn't really say anything about whether what he was preparing was good or bad.
H.M.: Well, taking it as
S.C.: They approved of the fact that he was just doing it.
H.M.: Well, that's one meaning.
S.C.: See what I mean?
H.M.: Yeh.
S.C.: They thought it was a good idea that he was . . .
H.M.: Yeh.
S.C.: that he was, um,
H.M.: Yeh, that's one way.
S.C.: spending his time in this manner.
H.M.: Yeh.
S.C.: And it doesn't really matter whether what he was making was good or bad. Do you see that or not?
H.M.: Yes, in a way. Uh, just that Mary and I approved of it, that Mary and I is the only ones right there
S.C.: Uhmmm.
H.M.: and
S.C.: It, but it, you see in the first meaning they thought that what he was making was good to eat and
H.M.: Yeh.
S.C.: in the second meaning they thought it was good that he was doing that regardless of what it turned out like.
H.M.: His way.
S.C.: Just the fact that he was doing it was a good thing.
H.M.: The way he was doing it.
S.C.: They approved of it, they think that men should cook, you see.
H.M.: Uh, I was thinking of the way he was cooking.
S.C.: Yeh, but the second meaning doesn't have anything to do with the quality of the food or how good it tastes. It just says that it was a fine idea that he was doing that. Period. You see?
H.M.: Well, yes, I see. I know what you mean now on that one.

understand what you mean by that.'' *Interactional interjections* served either to encourage H.M., e.g., ''Uhmm,'' and ''That's very good,'' or to segment the trials, e.g., ''Okay. Here's the next sentence.''

### *Results*

To provide in-context examples of features that we subsequently analyzed quantitatively, Tables 2a,b,c present the complete transcript of H.M. and controls for three of the 32 experimental sentences: *The marine captain liked his new position; He told me to go without any hesitation*; and *Mary and I approved of his cooking*. We chose these sentences as representative of the three types of ambiguous sentences (lexical, surface structure, and deep structure), and as occurring at non-initial and non-final points spaced throughout the experiment, i.e., positions 4, 15, and 29 in the sequence of 32 (mean position 16). Also, H.M.'s responses to these sentences were typical of his other responses in median length and in global characteristics such as grammaticality and coherence (discussed in Study 2). Corkin's interjections for these sentences were also typical of her interjections throughout the experiment.

#### *Communicative Effectiveness*

We developed two measures of communicative effectiveness in this task. One was the frequency of Assistance, Elaboration, and Clarification interjections: We viewed responses as less effective if the experimenter could not understand them, required elaboration in order to understand them, or otherwise had to assist the speaker in expressing the two meanings of an ambiguous sentence. Our second measure of communicative effectiveness

TABLE 3

Mean Number of Experimenter Interjections per Response for H.M. and Controls in Study 1, with SD in Parentheses (see Text for Definitions of Interjection Types)

| Interjection type | H.M. | Controls (mean) | Control 1 | Control 2 | Control 3 |
|---|---|---|---|---|---|
| Assistance | 3.94 | 0.29 (0.20) | 0.41 | 0.39 | 0.06 |
| Elaboration | 4.06 | 0.68 (0.51) | 1.13 | 0.77 | 0.13 |
| Clarification | 0.23 | 0.03 (0.03) | 0.03 | 0.06 | 0.00 |
| Reminder | 1.25 | 0.00 (0.00) | 0.00 | 0.00 | 0.00 |

was *ambiguous reference*, e.g., use of key ambiguous words from the stimulus sentences *without disambiguation.* Such uses reduced communicative effectiveness by making it difficult to tell what meaning the speaker was referring to, or even to tell whether the speaker had comprehended both meanings of the ambiguity.

*Interjections.* Table 3 shows the mean number of Assistance, Elaboration, and Clarification interjections per response for H.M. and controls, together with variance in standard deviations. These interjections were each more common for H.M. than for controls by over 6 standard deviations, with H.M.'s mean well outside the range for controls (see Table 3). Reminder interjections were likewise more common for H.M. (1.25 per response) than for controls (0), but this difference is consistent with both ''pure-memory'' and NST accounts.

*Ambiguous reference.* Ambiguous reference refers to use of words and phrases with no clear referent, and fell into two categories. Type I ambiguous reference did not involve ambiguous words from the stimulus sentences. For example, in explaining why the marine captain liked his new position, H.M.'s referent for *them* and *of all* is unclear in ''because he was above them and of all, most of all . . .'' (see Table 2a). Type II ambiguous reference involved use of key ambiguous words from the stimulus sentences without disambiguation. For the sentence, *The marine captain liked his new position,* H.M. repeated the ambiguous word *position* five times without disambiguation, whereas controls used the word *position,* but never ambiguously (see Table 2a; also Table 2bc). In analyzing Type II ambiguous reference, we did not count instances where speakers stuttered or immediately repeated an ambiguous word, or deliberately read or quoted the original sentence, or quoted their own prior use of an ambiguous word following an interruption. Type II ambiguous reference generally induced calls for clarification to enable Corkin to determine which meaning H.M. was describing (see Tables 2a,b,c), but not always: When Corkin explained the two meanings of *position* to H.M. in Table 2a (*One has to do with his job and the other is if he is sitting, standing or whatever*), and H.M. immediately used the word *position* ambiguously again for the fifth time (*The position he's in*), Corkin simply corrected him (*The position of his body*). Overall, ambiguous reference was more common for H.M. (M = 78.0) than for controls (M = 16.9), a difference reliable at $p < .001$ using a sign test with sentences as unit of analysis.

### *Communicative Repetition*

Five different types of repetition stood out in a close inspection of H.M.'s transcript: Repetition of clichés (stock phrases and propositions); repetition of ambiguous words from the stimulus sentences; repetition of H.M.'s initial interpretation of an ambiguous sentence; repetition of words during attempts to rephrase, e.g., what he himself had said; and echoing or concurrent repetition of what Corkin was saying.

*Repetition of formulaic phrases.* As predicted under NST, H.M. tended to repeat clichés or formulaic phrases more frequently than controls. Table 4 organizes H.M.'s fre-

TABLE 4

Prototype Expressions (and Their Variants) that H.M. Frequently Repeated in Corkin (1973) and Marslen-Wilson (1970)

| Prototype expressions | Variants |
|---|---|
| I thought of | I think of<br>I would think of<br>I also think of<br>I was thinking of<br>I'm thinking |
| You'd call it | You could call it<br>You'd say<br>You'd put it that way |
| I have an argument with myself | I have a debate with myself<br>I have a mental reservation |
| I guess<br>I wonder<br>In a way<br>Well<br>Naturally<br>Right off | |

quently repeated clichés into prototypes (the form used most frequently) and their (less frequent) variants. An example prototype was the expression ''I thought of,'' with its variants, ''I think of'', ''I would think of'', ''I also think of'', ''I was thinking of'', and ''I'm thinking'' (see the underlined examples in Tables 2a,b,c). What was surprising was how often H.M. used such stock phrases in Corkin (1973), i.e., 93 *I-thought-of*s, or almost 3 per response ($SD = 2.16$). However, we were unable to detect repetition by controls of these or any other phrases throughout the entire experiment, a difference reliable at $p < .001$ using a sign test with sentences as unit of analysis.

*Ambiguous word repetition.* This analysis counted all repetitions of ambiguous words from the stimulus sentences, regardless of whether the speaker disambiguated the words, stuttered or immediately repeated the words, deliberately read or quoted the original sentence, or quoted their own prior use of an ambiguous word following an interruption. For example, H.M. repeated the ambiguous words *his cooking* in the sentence, *Mary and I approved of his cooking,* twenty-five times, whereas Control 3 repeated *his cooking* zero times (see Table 2c; also Table 2ab). Ambiguous word repetitions were more common for H.M. ($M = 7.37$ per response) than for controls ($M = 2.78$ per response), a difference reliable at $p < .03$ using a sign test with sentences as unit of analysis. This difference is especially remarkable because Corkin repeatedly asked H.M. to avoid using ambiguous words from the sentences (see Table 2c).

*Proposition-level repetition.* Proposition-level repetitions involved reiteration of the same interpretation of an ambiguity: H.M. described one of the meanings of a sentence and then described this same meaning again, often several times, with as many as eight repetitions of the same meaning within a single response (see Table 2c). In Table 2a, for example, H.M. restated the ''job'' meaning of *position* three times before Corkin gave up and told him the ''physical'' meaning of *position.* Many of H.M.'s proposition-level repetitions seemed deliberate because they were immediate, or followed only a few seconds after H.M.'s initial description (see Table 2ab), and they overrode negative feedback from the experimenter: Corkin often drew H.M.'s attention to these repetitions and explicitly asked him to give a different meaning, but H.M. nonetheless immediately repeated the same meaning again (see Table 2ab). Interestingly, many of H.M.'s proposition-level repetitions were also word-for-word, as when H.M. said, ''personally he doesn't like them and and personally he doesn't like them'' in explaining the meanings of the sentence, I *just don't feel like pleasing salesmen.* Proposition-level repetitions were more common for H.M. (1.50 per response) than for controls (0.31 per response), a difference reliable at $p < .03$ using a sign test with stimuli as unit of analysis.

*Rephrasing repetition.* Rephrasing repetitions involved repetition of several words unrelated to the ambiguity or to H.M.'s interpretation of the ambiguity. Examples from H.M.'s response to the sentence, *The stout major's wife stayed home* are, ''She stayed home, *she stayed home* or was not moving around. . . .'' ''Then, uh, sort of, or made to, or to stay at home was *to stay*, not go out, not leave . . . (repetitions in italics).'' Although deliberate and immediate, H.M.'s rephrasing repetitions differed from ambiguity-related repetitions in three respects: They were less common than ambiguity-related repetitions, they never generated negative feedback from the experimenter, and they seemed to reflect attempts to rephrase the stimulus sentences, or to rephrase what he himself was saying (see Table 2c). The mean number of rephrasing repetitions was 1.47 or 3.13 repeated words per response for H.M. versus 0.0 for controls, a difference reliable at the .001 level with stimulus sentences as unit of analysis.

*Echoing repetition.* At several points, the transcript labeled H.M.'s output as ''echoing,'' i.e., concurrent, nearly verbatim repetition of what Corkin was saying. For example, Corkin concluded her explanation of the two meanings of *Those who play chess as well as Bill came,* with ''as good as Bill is, came'', accompanied by H.M.'s echo, ''as Bill is, they came'' (see also Table 2c). No instances of echoing were observed in the responses of controls.

### Are H.M.'s Production Deficits Motivational?

In view of established relations between limbic structures and motivation, initiative, and affect (for reviews, see, e.g., Gray, 1982; Hebben, Corkin, Eichenbaum, & Shedlack, 1985; O'Keefe & Nadel, 1978), we wanted to ensure that H.M.'s performance in the present task did not reflect lack of motivation. We therefore compared how many words H.M. and controls used in describing the two meanings of the sentences as an initial measure of motivation. Mean number of words per response averaged across the 32 sentences was more than 11 standard deviations greater for H.M. than controls, with H.M.'s mean lying well outside the range for controls (see Table 5). A second analysis examined how many words H.M. and controls used prior to the first Elaboration interjection by their experimenters. H.M. used 57.7 words per response prior to the first Elaboration interjection, whereas controls used 31.1, a difference of more than two standard deviations, with H.M.'s mean again falling well outside the range for controls (see Table 5). These data indicate that independently of calls for elaboration, H.M. generated more words than controls, suggesting that he was at least as motivated as controls to communicate about the ambiguities and to succeed in this task, despite evidence of failure (see Tables 2a,b,c). Consistent with this interpretation, H.M. expressed clear frustration with his failures to communicate the two meanings of the sentences to Corkin in Study 1 (see, e.g., Table 2a: ''I just gave you two''). A detailed reading of the transcript also indicates that H.M. remained focused on the task or goal, with no tendency to intrude entirely new and unrelated topics of discussion due to boredom or waning motivation (see Tables 2a,b,c).

### Communicative Conciseness

By the preceding analyses, H.M. tended to repeat and was less concise than controls in describing the two meanings of ambiguous sentences. To test whether H.M. was less concise independent of his repetition tendencies, we compared how many words H.M. and controls used prior to the first ''Elaboration'' interjection, excluding the repetitions discussed earlier. By this analysis, H.M. used 53.4 words per response, whereas controls used 29.9 (see Table 5), a difference reliable at $p < .001$ using a sign test with stimulus sentences as unit of analysis, with H.M. again well outside the range for controls. Although not due to H.M.'s repetition tendencies, or to Corkin's calls for elaboration, this difference may reflect H.M.'s attempts to restate his ideas more coherently using different words (see, e.g., Table 2c).

## Discussion

Present data contradict the prevailing view that H.M. has a pure memory deficit, and that his language production processes are completely normal. For example, it is difficult to

TABLE 5

Mean Number of Words per Response for H.M. and Controls in Study 1 (Overall and Prior to the Experimenter's First Elaboration Interjection), with SD in Parentheses

| | H.M. | Controls (mean) | Control 1 | Control 2 | Control 3 |
|---|---|---|---|---|---|
| Words per response (overall mean) | 188.7 | 43.1 (12.23) | 47.4 | 52.6 | 29.3 |
| Mean words prior to first elaboration interjection | 57.7 | 31.1 (12.4) | 30.3 | 36.0 | 27.0 |
| Words prior to first elaboration interjection excluding all repetitions | 53.4 | 29.9 (12.5) | 28.4 | 34.4 | 26.6 |

ascribe the reduced effectiveness of H.M.'s descriptions to forgetting the stimulus sentences, which were short, syntactically simple, and perceptually available to H.M. throughout the task. Nor is it likely that H.M.'s proposition-level repetitions reflected inability to remember his initial meaning descriptions: H.M.'s prior sentence often occurred only a few seconds earlier, and should have fallen well within his normal forgetting functions (Freed et al., 1987; Freed & Corkin, 1988) and normal short-term memory span (e.g., Wickelgren, 1968). Although rapid forgetting can occur with computer compressed sentences (MacKay & Miller, 1996b; Miller & MacKay, 1996) and with an unexpected memory test for meaningless trigrams presented in a complex dual task paradigm (Muter, 1980), adults with normal short term memory do not forget their own sentential output so rapidly (Kintsch, Welsch, Schmalhofer, & Zimny, 1990).

### *What Aspects of Language Production Are Impaired in H.M.?*

Under NST, it is significant that when H.M. repeated clichés, he didn't just repeat a rote phonological structure. For example, he used many different ''I-thought-of'' variants rather than just one identically repeated three-word phase. This pattern fits the NST hypothesis that H.M.'s deficit involves the semantic level of speech production, but not the phonology or muscle movements for articulating speech. That is, H.M.'s binding deficit makes it difficult to concatenate novel semantic information, and to form the semantic-level connections needed for expressing creative ideas, but does not impair his expression of old or familiar ideas via clichés and their variants. Under NST, H.M. has no deficit in the use of connections for producing the muscle movements, phonology, syntax, and meaning for familiar concepts because these connections were formed and highly practiced prior to his brain lesion.

To further illustrate the dissociation between H.M.'s intact use of old connections versus impaired ability to form new ones, consider H.M.'s ability to recall his birth date versus his age. H.M. can quickly and accurately report his year of birth via a proposition such as ''I was born in 1926'' (Ogden & Corkin, 1991) because the readily activated connections representing this proposition have been formed long before his brain lesion and have been strengthened over a lifetime of use. However, H.M. has difficulty reporting his age (Ogden & Corkin, 1991) because propositions such as ''I am 43'' require the formation of new connections to accurately represent his age each year, and to inhibit activation of the old connections representing his age in previous years.

The distinction between using old connections versus forming new ones also makes sense of Sidman et al.'s (1968) delayed matching-to-sample data, where H.M. was impaired for ellipses but not for trigrams. H.M. could readily rehearse a pronounceable trigram during the delay interval and respond to that trigram at test without having to form new connections. However, ellipses of differing size cannot be rehearsed without forming a new connection to tag an ellipse as, e.g., ''next-to-largest,'' a process made difficult by H.M.'s binding deficit.

*H.M.'s Repetition Tendencies*

NST accounts for H.M.'s five types of repetition via three related categories of explanation that derive in various ways from his binding deficit. The Category I account addresses rephrasing repetitions: Because of his problem in forming the new semantic-level connections required to represent coherent propositions, H.M. repeatedly rephrased what he was saying in an attempt to achieve greater coherence.

The Category II account addresses repetition of clichés or familiar phrases. Under this account, H.M. repeated familiar phrases more often than memory-normal controls in order to minimize how many new connections he must form during language production. That is, by reducing his ability to represent new ideas, H.M.'s binding deficit may be directly related to his increased use of highly accessible formulaic phrases represented by nodes and connections formed prior to his operation and strengthened throughout a lifetime of use. Why H.M. so often began his responses with ''I thought of'' is of course another question, but it is noteworthy that stutterers often use self-chosen ''starter phrases'' of a remarkably similar nature in trying to overcome their (quite different) production deficit (van Riper, 1982, pp. 136–7).

The Category III account addresses H.M.'s echoing, repetition of ambiguous words, and immediate repetition of his initial interpretation of the sentences. Under this account, H.M.'s operation forced him to develop a deliberate and habitual rehearsal strategy to compensate for his binding deficit via engrainment learning processes. Memory-normal individuals exhibit this same rehearsal strategy when connection formation is difficult, as when unrelated nouns are rapidly presented for later recall without cues to how they should be grouped or linked together. The difference is that H.M. also required this rehearsal strategy when connection formation is easy, as when familiar syntactic rules or strategies guide the connection formation process for comprehending and producing coherent sentences. H.M.'s echoing repetitions reflect this rehearsal strategy for forming new connections during on-line language comprehension, and his repetition of ambiguous words and propositional interpretations reflect this rehearsal strategy for forming new connections during language production. That is, H.M. immediately repeated ambiguous words and propositions because he was deliberately substituting engrainment learning for hippocampal binding in order to form and strengthen the new connections for representing the two meanings of ambiguous sentences.[5] This explains why H.M. was especially likely to repeat ambiguous aspects of the sentences: More new connections are required to represent ambiguous than unambiguous aspects of sentences in the present task (see Figure 4).

Also consistent with a habitual rehearsal strategy, H.M. has elsewhere exhibited remarkable tendencies to rehearse and to sustain rehearsal. Without instructions to do so, H.M. on one occasion rehearsed (and successfully recalled) a string of random digits for an hour or more after an experimenter was inadvertently called away (Ogden & Corkin, 1991). On another occasion, H.M. spontaneously noted and rehearsed for an extended period the exact time at which an experimenter left the room (2:05PM; Ogden & Corkin, 1991). Although the tasks at hand may have contributed to these remarkable feats of repetition, no such explanation applies to the present study, where H.M.'s repetitions of clichés, words, phrases, and propositions were completely spontaneous, and often provoked negative feedback from the experimenter.

A rehearsal strategy may also underlie other spontaneous repetition tendencies that have

[5] Proposition-level repetitions that fall outside H.M.'s normal short term span (over fifteen words for sentences) may have occurred for another reason related to his binding deficit: H.M.'s difficulty in forming new connections for ''tagging'' what he has said as ''already described'' may have caused him to inadvertently repeat the same proposition again in these cases.

been observed in H.M. and other amnesics (see, e.g., Squire, 1987, p 179): H.M. has been known to repeat the same sentence many times a day (Hilts, 1995, p. 136), and to repeat whole stories nearly verbatim on different occasions (Ogden & Corkin, 1991). This story repetition pattern has been attributed to H.M.'s inability to remember whether he previously told the same story to the same listener, but this account does not explain why H.M. uses virtually the same concepts and grammatical structures when he repeats a story from one occasion to the next.

We now examine two alternative accounts of H.M.'s repetition tendencies. One explains H.M.'s repetitions in terms of a general tendency to perseverate. However, contrary to this general perseveration hypothesis, H.M. makes an unusually small number of perseverative errors on the Wisconsin Card Sort task, a standard test of perseveration tendencies (Milner, 1963). A second alternative account applies only to H.M.'s rephrasing repetitions. Under this hypothesis, H.M.'s semantic-level planning or connection formation processes are intact, but he tends to make speech errors, i.e., his speech inadvertently deviates from his preformed plan. This preformed plan enables H.M. to detect his errors, and he persistently tries to correct them, rephrasing what he has said and repeating himself in the process. To concretely illustrate this ''error correction'' account of H.M.'s rephrasing repetitions, assume that H.M.'s expression ''and then marine captain he liked the new position'' (see Table 2a) contains two errors: omission of the word ''as'' and omission of appropriate prosodic pauses, so that H.M.'s intended output was the grammatical, ''and then, as marine captain, he liked the new position'' (see Example 1, below, where the intention precedes an arrow standing for ''was misproduced as''). Example 2 likewise represents H.M.'s continuation, ''he liked the new position because of being, being a passenger line'' (see Table 2a), as a complex series of semantic-level deviations from his hypothesized intended utterance preceding the arrow. Example 3 is a hypothetical illustration of how a normal speaker would correct the ''error'' to the right of the arrow in Example 2.

Example 1. and then, as marine captain, he liked the new position (hypothesized intended utterance) → ''and then marine captain he liked the new position.'' (actual ''erroneous'' output)

Example 2. he liked the new position because of it's being on a passenger line (hypothesized intended utterance) → ''he liked the new position because of being, being a passenger line'' (actual ''erroneous'' output)

Example 3. ''he liked the new position because of being, being a passenger line'' (putative ''error'') → er, I mean, because of it's being on a passenger line (hypothetical error correction typical of normal speakers)

Like NST, this ''error correction'' account of H.M.'s rephrasing repetitions contradicts stages-of-processing theories and the prevailing view of H.M.'s condition. However, several aspects of the data are problematic for this error correction account. First, H.M. never corrected his ''errors'' in the manner of normal speakers illustrated in Example 3. For instance, H.M. never generated ''repair signals'' such as *I mean, rather, er,* and *um* that normally accompany error corrections (Levelt, 1989, pp. 478–492). Also problematic for the error correction hypothesis, an acceptable ''correction'' or model provided by the experimenter should have enabled H.M. to ''move on'', but this was not the case: As can be seen in Table 2a, H.M. continued to reiterate the ''job'' meaning following Corkin's ''he liked his job in other words'', as if he was unwilling or unable to ''tag'' that meaning as ''already described''. Even when the experimenter indirectly requested that H.M. move on (see Table 2a: ''That's one meaning''), H.M. did not move on (see also Table 2bc).

## STUDY 2: GLOBAL MEASURES OF H.M.'S LANGUAGE PRODUCTION FROM CORKIN (1973)

Study 1 provided indirect measures suggesting that H.M. was less effective in his communication than memory-normal controls. Study 2 more directly examined H.M.'s communicative effectiveness in the Corkin (1973) transcript by having naive judges rate the language output of memory-normal controls and H.M. on three global dimensions: comprehensibility (ease of understanding), grammatical correctness, and coherence (degree of focus, tangential or off-topic speech). NST predicted higher ratings on all three dimensions for memory-normal controls than for H.M., whereas stages-of-processing theories predicted no difference on all three dimensions.

### *Method*

*Participants.* The main participants were six naive ''judges,'' college students or former college students (aged 18–21) who were paid to provide ''blind'' ratings of response excerpts from H.M. and the controls in Study 1.

*Materials.* Materials were 128 excerpts consisting of the longest uninterrupted stretch of speech produced by H.M. and controls for each of the 32 sentences (see Tables 2a,b,c for example excerpts). This excerpt criterion served to equate number of words more closely for H.M. and controls, and to eliminate possible effects of experimenter interjections on the ratings.

*Procedures.* Each judge rated the 128 excerpts in individual sessions. Judges knew that different speakers had produced the excerpts when describing the two meanings of ambiguous sentences, and that they were to compare all four excerpts for a given sentence, and use a seven-point scale to answer one of three questions for each excerpt: ''How easy was the excerpt to understand?'' (1 = ''not at all'' understandable'' to 7 = ''completely'' understandable); ''How grammatically correct was the excerpt?'' (1 = ''major violations of grammar'' to 7 = ''no violations of grammar''); and ''To what extent did the respondent stay focused on the topic?'' (1 = ''not at all'' focused or on topic'', to 7 = ''completely'' focused on topic''). Instructions emphasized that judges were rating *excerpts* and that they were to focus exclusively on how what was said was said, ignoring other factors such as number of words or what they might judge to be a complete or adequate response.

The 32 stimulus sentences were divided into three groups based on presentation order in Corkin's experiment, and a different rating dimension was assigned to each sentence group, with assignment of rating dimensions to sentence groups counterbalanced across judges. Each judge received 32 sheets of paper, each headed by a different ambiguous sentence, followed by typed instructions for one of the rating scales, blocked by sentence group. Next came the response excerpts of H.M. and the controls in differing random orders for different judges. Each excerpt was labeled with a different capital letter in recycling alphabetic order across the 128 excerpts to discourage judges from developing biases across trials based on inferred speaker identity.

### *Results and Discussion*

Table 6 shows mean ratings for H.M. and controls, with 7 as maximal score for comprehensibility, grammaticality, and focus (i.e., lowest off-topic speech). Controls received higher ratings than H.M. on all three dimensions. With the six judges as unit of analysis, paired t-tests between the mean ratings for H.M. and the controls indicated significantly higher ratings for controls than for H.M. in comprehensibility, $t(5) = 5.34$; in grammaticality, $t(5) = 5.96$; and in focus, $t(5)5.21$, all $p$'s $< .01$.

Before considering theoretical implications of these grammaticality, focus, and comprehensibility results, it is important to examine what detailed aspects of H.M.'s speech these global measures might reflect. To illustrate some of these aspects, consider H.M.'s response to the sentence *The marine captain liked his new position* in Table 2a. H.M. begins, ''he liked the new position on a boat that he was in charge of, the size and kind it was,'' introducing a subtle within-sentence switch of topic or focus from *liking his position* (topic 1) to *liking the size and kind of boat he was in charge of* (topic 2). When H.M. continues, ''. . . because he was above them and of all,

TABLE 6

Means (and Standard Deviations) for Ratings of Comprehensibility, Grammaticality, and Focus for Excerpts from H.M. and Controls in Study 2

| Rating dimension | H.M. | Controls (mean) | Control 1 | Control 2 | Control 3 |
|---|---|---|---|---|---|
| Comprehensibility | 2.60 (.55) | 3.97 (0.66) | 3.39 (.50) | 3.84 (.60) | 4.69 (.55) |
| Grammaticality | 2.04 (.40) | 3.99 (0.62) | 3.27 (.80) | 4.24 (.74) | 4.47 (.71) |
| Focus | 3.15 (.93) | 4.61 (0.40) | 4.37 (.46) | 4.40 (.46) | 5.07 (.29) |

most of all . . .'', the referents for ''them,'' ''of all,'' and ''most of all'' are unclear or difficult to interpret (the comprehensibility dimension). Indeed, H.M.'s ''most of all'' is clearly a free association to his immediately preceding ''of all'' that is relevant to all three rating categories: it is incomprehensible (the comprehensibility dimension); it is ungrammatical (the grammaticality dimension); and it is off-topic (the focus dimension). H.M.'s subsequent, ''he was a marine captain of a boat there and then marine captain he liked the new position because of being, being a passenger line'' (see Table 2a) illustrates further problems with focus, comprehensibility, and grammaticality. This example also illustrates a problem with categories such as ''sentence'' and ''paragraph'' for describing H.M.'s output: Where one sentence or paragraph leaves off and where the next begins was often difficult to determine in H.M.'s responses.

It seems unlikely that H.M.'s low coherence ratings were entirely attributable to ''forgetting from short term memory'': H.M.'s topic shifts, e.g., from *liking his position* (topic 1) to *liking the size and kind of boat he was in charge of* (topic 2), or from *above them and of all* (topic 1), to *most of all* (topic 2) usually occurred within a single brief sentence (see Table 2a) that would fall well within his normal forgetting functions (Freed et al., 1987; Freed & Corkin, 1988) and normal short term memory span for immediate repetition of sentential materials (over 15 words). It also seems unlikely that transcription errors contributed significantly to the problems of focus, comprehensibility, grammaticality and run-on sentences in H.M.'s speech. Corkin's transcript was extremely detailed and painstaking. Even the ''missing commas'' in ''and then marine captain he liked the new position'' (see Example 1 above) denote a significant production problem rather than a transcription problem: As Milner et al. (1968) noted, H.M. ''speaks in a monotone'' that deletes comma-pauses and other prosodic cues to his intended syntax. In addition, general transcription problems should have affected Corkin's responses, but whereas virtually all of H.M.'s responses raised issues of focus, ungrammaticality, incomprehensibility, and run-on sentences, none of Corkin's did so (see Tables 2a,b,c).

## STUDY 3: GLOBAL MEASURES OF H.M.'S LANGUAGE PRODUCTION IN MARSLEN-WILSON (1970)

Study 3 tested whether H.M.'s production deficits are specific to processing ambiguous sentences, or apply more broadly to conversational speech. Speech for Study 3 was produced in a conversational setting in response to questions about early childhood experiences that took place before H.M.'s operation and the head injury at age 9 that may have triggered his epilepsy. Analytic procedures resembled Study 2: Naive judges rated the conversational speech of H.M. and six memory-normal controls for degree of focus, comprehensibility, and grammaticality. NST predicted higher ratings on all three dimensions for memory-normal controls than for H.M. due to his semantic-level production deficits, whereas stages-of-processing theories predicted equivalent ratings for H.M. and memory-normal controls on all three dimensions because under these theories H.M.'s memory functions are intact for events stored prior to age 12–16 (e.g., Sagar et al., 1988), and because his memory storage deficit after age 27 is independent of language production.

### Method

*Participants.* Main participants were Controls 2-7 in Table 1, plus 10 naive ''judges'' who had not participated in Study 2. Judges were students or former students (age 20-23 years) who received payment for providing ''blind'' ratings of transcripts for H.M. and controls. Because H.M. was 44 when tested in 1970, he was three years younger than controls (see Table 1), a factor that should favor H.M. on the coherence dimension (Arbuckle & Gold, 1993).

*Materials and procedures.* From the many autobiographical questions that H.M. answered in his tape recorded conversations with Marslen-Wilson (1970), we selected all available ones that met the following criteria:[6] First, the questions addressed events or information known to H.M. from personal experience prior to age six, well before his bicycle accident at age nine that may have triggered his epilepsy. Second, H.M.'s answers to the questions were self-contained, free from interruptions of any sort, free from phrase and sentence repetitions, free from transcription difficulties (indicated via question marks in the transcript), and relatively brief (enabling a rating session of reasonable duration). Only two questions met these criteria: *Do you remember any of the kids in your kindergarten?* (a question encompassing multiple episodes involving one or more fellow kindergartners); and *What is your first memory, the earliest thing you remember?* (a question encompassing a single episode or event). Materials for Study 3 therefore consisted of the full verbatim answers by H.M. and controls to these questions (see Table 7 for exact wording).

[6] When we ran Study 3, only part of the Marslen-Wilson transcript was available to us. However, we obtained the full 144 page transcript after completing Study 3, and the examples in Table 9 all come from the previously unavailable corpus.

As per Marslen-Wilson's procedures, the six controls answered these questions in the laboratory in one-on-one conversations that were embedded within a larger autobiographical context. One minor difference concerned H.M.'s ''kindergarten'' question: The experimenter first asked whether controls had attended kindergarten, and if not, rephrased this question to refer to ''kids in first grade''. Conversations with controls were tape recorded and later transcribed as in Marslen-Wilson (1970) and Study 1. Table 7 shows the full responses for H.M. and half the controls for each question.

*Rating procedures.* Procedures and dimensions for rating were identical to Study 2 except that all judges rated the full responses to both questions on all three dimensions for H.M. and the six controls. Each judge received two ''stimulus sheets'', each containing a question followed by verbatim answers of all seven alphabetically labeled and randomly ordered speakers, plus two ''response sheets,'' each containing instructions and scales for rating the comprehensibility, focus, and grammaticality of each answer.

### Results and Discussion

Table 8 shows the mean ratings for conversational speech materials of H.M. and controls, with 7 as the best possible score for comprehensibility, grammaticality, and focus. Using paired t-tests with the 10 judges as unit of analysis, mean ratings for controls were significantly higher than for H.M. on all three dimensions: focus, $t(9) = 51.78$; comprehensibility, $t(9) = 31.55$; and grammaticality, $t(9) = 11.21$, all $p$'s $< .001$. Ratings for each individual control were also higher on all three dimensions than for H.M., smallest $p < .001$.

It is difficult to attribute H.M.'s low ratings to problems with Marslen-Wilson's British accent because H.M. claimed familiarity with this accent since age seven when his uncle ''married an English woman'' and because H.M. neither asked Marslen-Wilson to repeat questions nor otherwise indicated comprehension difficulty at any point in the transcript. Nor was our response sample unrepresenta-

TABLE 7

Full Responses of H.M. and Half the Controls to the Two Conversational Speech Questions in Study 3

Question: ‘‘I wonder . . . Now that we’re talking about this early time when you were going to kindergarten, what do you think is the earliest thing you remember, your first memory?’’

Control 3: Oh, way back, uh . . . two. I was two because I have seen pictures of myself in a snowsuit, and I outgrew it very quickly, but when I was two I wore it and when I was two I remember walking in my grandma’s kitchen and pointing up at my snowsuit hanging on the kitchen door because I wanted to put it on, and it’s very clear—it was light blue.

Control 5: Believe it or not, my first memory, I was about two and a half years old, and I can remember waking up in my crib at my grandparents’ apartment, and seeing all the adults out in the dining room from the bedroom area, and they were all having so much fun, and I can remember going, and I want to be there too. That’s my very first cognizant memory.

Control 7: Oh, I remember playing with my sister and brother.

H.M.: When I . . . tell you that ‘tis . . . you see . . . may have been . . . that was when I was going to high school . . . that . . . and . . . but before that when I was going to the private kindergarten, two houses up, from where I lived, when I went to high school, but the other places I lived in Hartford, and Manchester, and then South Coventry . . . before coming back to (chuckles) Burnside Avenue again.

Question: ‘‘Do you remember any of the kids there (in kindergarten)?’’

Control 2: Not really—can’t remember any of them.

Control 4: None in kindergarten. I don’t remember. I had, um . . . cause I don’t know if it’s kindergarten, first grade. I remember a couple of other children.

Control 6: Uh huh. Actually, I went through most of the school with the same people, so I remember, yeah, all of them really.

H.M.: Uh, just . . . uh . . . was a private kindergarten, and being on Burnside Avenue, and we . . . my mother would take me down . . . Burnside Avenue to . . . uh . . . can’t think of the name of the street . . . but where the drugstore was, and we’d gather there, the kids, all of us kids and then we’d . . . the teacher that was . . . taking us down to the private kindergarten, would take us down there . . . that way and . . . because there were . . . from different areas and that was one of the . . . that was one of the main . . . spots, the northern spot . . . I say northern but it isn’t northern, it’s east . . . uh . . . the collect . . . area, we’d gather at that area, she’d take us down, then she’d have to and . . . her mother . . . would . . . not she, her mother (emphasis in original) would be collecting the kids on . . . uh . . . the west . . . so . . . they’d come together and meet . . . naturally all meet in the same house.

TABLE 8

Means (with Standard Deviations in Parentheses) for Ratings of Comprehensibility, Grammaticality, and Focus for Conversational Speech of H.M. and Six Memory-Normal Controls in Study 3

| Rating dimension | H.M. | All Controls (mean) | Control 2 | Control 3 | Control 4 | Control 5 | Control 6 | Control 7 |
|---|---|---|---|---|---|---|---|---|
| Comprehensibility | 0.95 | 5.12 | 4.95 | 5.35 | 4.25 | 5.05 | 5.10 | 6.00 |
| | (0.44) | (0.43) | (0.80) | (0.78) | (0.76) | (0.76) | (0.84) | (0.00) |
| Grammaticality | 1.50 | 4.40 | 3.60 | 5.20 | 3.70 | 4.20 | 3.85 | 5.85 |
| | (1.0) | (0.44) | (0.94) | (0.72) | (0.63) | (0.89) | (0.67) | (0.47) |
| Focus | 0.35 | 5.21 | 5.45 | 5.6 | 4.65 | 4.50 | 5.10 | 5.95 |
| | (0.41) | (0.25) | (0.50) | (0.52) | (0.82) | (0.91) | (0.99) | (0.16) |

TABLE 9

Responses of H.M. to Additional Questions in Marslen-Wilson (1970)

Question 1: Why did she take over? (referring to a lay teacher who had apparently taken over grades 1 and 2 in H.M.'s Catholic school)

H.M.: Uh . . . so that they took . . . well . . . she . . . I say took over, and what I mean it as . . . that, as the kids progressed then they were able to . . . uh . . . they'd gone to a lay teacher . . . and they'd seen the nuns around, so when they moved to the grade, next grade, they would . . . they would naturally . . . uh . . . more eased . . . with being with the . . . uh . . . nuns than being scared . . . they were going in there as young kids, they'd be scared, right off in a way . . . but they see them around and understand them more.

Question 2: Do you remember anything about your grandfather?

H.M.: . . . And I was just going to say something about him . . . uh . . . because we live??? on first . . . and . . . I went to a private kindergarten, and when I got out, didn't have . . . I didn't go to school for a year, because we had moved then up . . . uh . . . to Laurel Park Heights . . . to take care . . . of him in a way . . . because my grandmother had died . . . or his wife . . . had died . . . it was on Laurel Park Heights that it . . . the house was at. . . .

Question 3: How are you feeling . . . tired?

H.M.: Well . . . I'm just wondering myself . . . now . . . well . . . when you fellows are taking this all down of course on tape . . . but I'm wondering just how it will be. . . .

WM-W: How do you mean, ''How it will be''?

H.M.: Well . . . just how I have spoken, how I sound, and what my answers are . . . and . . . uh . . . a a big question mark right there. . . .

Question 4: Now, Henry, I want to show you some pictures. I want you to see what you can tell me about them. . . . What do you think that's a photograph of? (referring to the footprint of an astronaut in lunar soil)

H.M.: . . . Well . . . there I have an argument with myself because I think of a tree right off, right there . . . when I saw it . . . and . . . but I think of the . . . ground, and this is some kind of a . . . a cast . . . that had been made . . . and I can't out of a shoe . . . of some kind . . . with those rivers that's all . . . and being round in the back there. . . . I drew the conclusion right off. . . .

Question 5: Why do you think that's funny? (referring to a cartoon of a distraught woman in the foreground saying, ''The Pill. The Pill,'' as she crawls out of a messy kitchen containing five young children (three squabbling with each other, one crying, one quizzical), dirty laundry, dishes and pots, and toys strewn over the floor. The woman's comportment resembles someone dying of thirst in the desert, crying ''Water! Water!'').

H.M.: . . . Well . . . it's a wonder of the . . . uh . . . the mother of course going out of the room . . . but seeing ''The Pill, the Pill'' and all the like soap suds in a way that there's been raised there (there were no soap suds) . . . she can't do anything, however, she has to do everything . . . she . . . both ways of lookin?? at it . . . as you could say . . . because the pots and everything.

WM-W: Why . . . What's the . . . why's she saying ''The Pill, The Pill''?

H.M.: She isn't saying ''The Pill, The Pill'' . . . it's the little girl that's saying to the boy.

WM-W: Oh, I see, yes . . . that's right . . . why's she saying it to the little girl . . . little boy?

H.M.: Well . . . to . . . point out to the boy that that's what it was that . . . the little pill that the mother possibly had dropped in to make the soaps??? and . . . and maybe . . . she thought maybe, well, it was more than one pill that she had put in, and that got . . . that's why she got so many.

tive: Marslen-Wilson's transcript contained similar production problems throughout. Examples are H.M.'s responses to Questions 1–5 in Table 9, which met our Study 3 criteria and came from other parts of the transcript (see footnote 6).

With respect to our original hypotheses, Study 3 data contradicted all three stages-of-processing predictions: equivalent coherence, grammaticality, and comprehensibility ratings for H.M. and memory-normal controls. Of course, it might be argued that H.M.'s low ratings stemmed from reduced ability to recall early memories. However, this hypothesis contradicts both the stages-of-processing account and the findings of Sagar et al. (1988), i.e., no difference in early autobiographical memory for H.M. and controls. It is also difficult to argue that H.M. was overconfident in his ability to recall, so that his low ratings reflected attempts to describe what he thought he could remember, but couldn't. Contrary to this hypothesis, H.M. frequently gave a simple ''No'' to the question, ''Do you remember'' throughout the Marslen-Wilson transcript.

It is also difficult to attribute H.M.'s low ratings to an inability to remember Marslen-Wilson's questions. For example, the question, *Do you remember any of the kids there in kindergarten,* should fall well within H.M.'s normal short term memory span (e.g., Corkin, 1984; Corsi, 1972; Wickelgren, 1968). However, H.M.'s answer to this question immediately began with off-topic references to his mother, the private nature of the kindergarten, and its location on Burnside Avenue, and never addressed the specific topic of fellow kindergartners (see Table 7).

Of course, once off topic, H.M. may not have been able to remember the original topic he was trying to address. Surprisingly, however, on five occasions in the transcript, Marslen-Wilson asked H.M. what they had been talking about following interruptions of various types and durations, and on all five occasions, H.M. was able to give an accurate answer. One such answer (''Indochina'') followed 14 speaker shifts or conversational turns involving over 133 words of irrelevant discussion about what time it was, whether H.M. was tired (i.e., Question 3 in Table 9), and how H.M. was helping science. Moreover, H.M. recalled this prior topic with no overt signs of rehearsal and despite inability to recall the name of the person he was talking to (W.M.-W) or the specifics of what had been discussed. Whatever his other encoding problems, H.M. could apparently encode and remember ongoing topics of conversation over remarkably long periods.

Study 3 data supported all three NST predictions: reduced coherence, grammaticality, and comprehensibility ratings for H.M. relative to memory-normal controls. H.M.'s language production problems therefore apply in a situation that closely resembles conversational speech, and cannot be fully explained in terms of task-specific processes associated with describing ambiguity. In addition, Study 3 results indicate that H.M.'s language production deficits extend to descriptions of preschool experiences for which H.M.'s memory functions are believed to be intact and independent of his epilepsy and epilepsy treatments (see, e.g., Sagar et al., 1988).

Also consistent with NST, we observed frequent use of formulaic phrases in conversational speech of H.M. in the Marslen-Wilson transcript, but not controls, and H.M. used the same formulaic phrases as in other transcripts (see Table 4; also quotations of H.M. in Hilts, 1995, pp. 235, 148, and 140; and Sidman et al., 1968). H.M. also used words with no clear referent and free associated to his own output in the Marslen-Wilson transcript, and in general, his responses were unclear: Consistent with experimenter interjection data in Study 1, Marslen-Wilson frequently asked H.M. to clarify or explain what he meant (see, e.g., Question 3 in Table 9). Also, as in Study 1, H.M.'s rated responses in Study 3 were less concise than those of controls (see Table 7), again independently of calls for elaboration or clarification.

However, H.M.'s speech differed in two respects in Study 3 versus Study 1. One concerned repetitions: Although rephrasing and cliché repetitions were common in H.M.'s conversational speech (see, e.g., Questions 1–3 in Table 9), immediate, proposition-level repetitions were virtually nonexistent in the Marslen-Wilson transcript. A second difference concerned word retrieval difficulties in H.M.'s conversational speech that were not apparent in Study 1, where H.M. had the stimulus sentences to guide his response. To illustrate these word retrieval difficulties, H.M.'s ''more eased'' in Question 1, Table 9, is presumably a neologism for the familiar, ''more at ease'' or ''more relaxed.'' Another example involves H.M.'s description of a model airplane made of ''. . . bamb . . . well I say bamboo, it isn't bamboo . . . it . . . uh . . . very like wood,'' as if he was unable to retrieve the word ''balsa.'' These retrieval difficulties suggest that H.M.'s ''slight anomia'' observed in Corkin (1984) may have been present in 1970. Similarly, H.M.'s deficits on tests of semantic and symbolic verbal fluency and on the reporter's test of language production (Corkin, 1984) may be part of the same pattern of deficits seen in his 1970-73 performance examined in the present research. In short, contrary to Corkin's ''premature aging'' hypothesis, all of H.M.'s language production problems reported in 1984 may have originated in 1953.

We turn now to an alternate, retrieval-deficit account of H.M.'s low ratings in Study 3. Under this hypothesis, H.M. has memory retrieval problems that extend to his earliest memories (contrary to the findings of Marslen-Wilson & Teuber, 1975, and Sagar et al., 1988), and his ungrammatical, unfocussed, and difficult to understand speech in Study 3 is entirely attributable to these hypothesized memory retrieval problems. Question 3 in Table 9 bears on this issue because it addresses H.M.'s current state of tiredness, so that neither memory retrieval nor references to memory played a role in H.M.'s unfocussed, off topic, and difficult to understand answer to this question (see Table 9). Also interesting in this regard were H.M.'s incoherent, unfocussed, and difficult to understand descriptions of 17 visually presented photographs and cartoons in Marslen-Wilson's corpus (see, e.g., Questions 4–5 in Table 9). Unfortunately, all 17 pictures referenced historical figures, events, or innovations (e.g., oral contraception) that gained fame after H.M.'s operation, making a ''pure memory'' account difficult to rule out. Nonetheless, H.M.'s picture descriptions indicated that H.M. is not reluctant to describe what he cannot remember (e.g., humans on the moon) or to invent an account for what he cannot comprehend (e.g., ''The Pill''). H.M.'s picture descriptions also suggest that his language production difficulties are not limited to answering questions that include the words ''memory'' or ''remember'' (see Questions 4–5 in Table 9).

A variant of the retrieval-deficit account of H.M.'s production problems might argue further that only a ''pure,'' retrieval-free measure of language production can test stages-of-processing theories. However, conversational speech is generally considered a prototypical language production task, and under distributed-memory theories, the assumption that there exist pure, memory-free measures of language production, or pure, production-free measures of memory is open to question. As Bock (1996, p. 400) points out, ''the standard ways of assessing both long- and short-term memory are tightly interwoven with the processes of normal language production'', and vice versa. Thus, production processes frequently have strong effects on long term recall of verbal materials, and the same is true of immediate recall: Unlike the traditional view that some pure memory process unloads, copies, or transmits from a short-term store (Pashler & Carrier, 1996), immediate recall more closely resembles the sequential assembly of highly activated linguistic units via normal language production mechanisms. This explains the close relation between immediate memory capacity and language production processes such as rate of articulation (e.g. Baddeley & Hitch, 1974; Schweickert & Boruff, 1986), the role in immediate memory tasks of language processes such as prosody (Miller & MacKay, 1996) and linguistic units such as noun phrases (MacKay & Abrams, 1994), and the distortions in short term recall that result from prior production of semantically related words (Lombardi & Potter, 1992).

## GENERAL DISCUSSION

### *H.M.'s Semantic-Level Production Deficits*

Seven results in Studies 1–3 indicate that H.M. suffered from a language production deficit in addition to his other deficits: H.M.'s responses were less grammatical, less comprehensible, and less focused or coherent than responses of controls in describing ambiguity (Study 2) and in conversational speech (Study 3), and as an indirect reflection of these production deficits, H.M. required more assistance, and elicited more requests for clarification and elaboration than controls in Study 1. Other characteristics of H.M.'s speech associated with reduced communicative effectiveness were his tendencies to use ambiguous words ambiguously, to repeat clichés or formulaic phrases, and to immediately repeat entire propositions. H.M. was also less concise than controls in describing the meanings of ambiguous sentences, independent of his repetition tendencies or of the experimenter's calls for elaboration. All seven deficits are independent of general age-linked declines: Present data were collected from 1970-1973 when H.M.'s IQ was at its highest levels (Corkin, 1984). Moreover, it is likely that H.M. had other language production deficits that were impossible to observe in the present transcript-based studies. One concerns the monotonous or aprosodic character of H.M.'s speech that Milner et al. (1968) noted, which suggests a deficit in the ability to produce the timing and stress cues that normally signal what words link together into phrases in sentences (see, e.g., Miller & MacKay, 1996).

All of H.M.'s production deficits contradict the general hypothesis that H.M. suffers from a pure memory deficit that has left his language production intact. All of H.M.'s production deficits also contradict the general stages-of-processing assumption that language production represents an autonomous processing stage with entirely separate units and processes from memory storage and retrieval. Present results also undermine more detailed stages-of-processing theories, e.g., the hypothesis of Squire (1987, pp. 151–169) and Cohen & Eichenbaum (1993, pp. 49–219) that procedural memory constitutes a distinct and separate store for generating learned skills. This separate-stores hypothesis was based on the assumption that H.M.'s cognitive skills are entirely intact, an assumption contradicted by H.M.'s deficits in the important cognitive skill of language production (see Shanks, 1996, for a review of other problems with the procedural memory hypothesis).

As already noted, however, the basic stages-of-processing framework is easily modified by subdividing one or more memory stores, or by adding new stores, and ad hoc modifications to fit the present data are readily imagined. For example, perhaps H.M.'s procedural memory is intact except for certain aspects of language production. Or perhaps H.M. has damage to a new type of memory system, say ''fluid working memory'' or ''executive intelligence'', that is essential for exactly those aspects of language production that are problematic for H.M.

Unlike stages-of-processing theories, however, NST requires no new or ad hoc assumptions to explain the present data. As predicted under NST, H.M. was less grammatical, less comprehensible, and less focused than normal controls in ambiguity descriptions (Study 2) and conversational speech (Study 3) because of his binding deficit, which forced him to use old but inappropriate connections, and hampered his ability to form new connections for representing propositions that were appropriate, coherent, grammatical, and comprehensible. For example, H.M. generated phrase-level free associations, e.g., ''above them and of all, most of all . . .'' in Example 4 (see also Table 2a), because *most of all* is a familiar phrase, and does not require new connection formation, unlike a coherent proposition-level description.

Example 4. ''of all'' (H.M.'s self-produced stimulus) → ''most of all'' (H.M.'s free association)

Example 5. ''he liked the new position (topic 1) on a boat, *the size and kind it was (topic 2)*''

Lacking connections required to represent coherent new propositions, H.M. also switched topics and focus, often within the same sentence, so that his sentences were not just ungrammatical, unfocussed and difficult to understand, but often lacked boundaries or seemed to fuse together. As in Example 5 above (see also Table 2a), H.M.'s topic shifts (in italics) were usually subtle rather than grossly tangential because the sentence on the card in front of him provided the general topic for H.M.'s responses.

By hypothesis, H.M.'s putative errors (see Examples 1–2) also reduced his grammaticality, focus, and comprehensibility ratings. However, unlike everyday errors in executing or enacting a coherent and well-formed sentential plan (see, e.g., Dell, 1986), H.M.'s errors occurred in the planning phase that normally precedes onset of production or execution. That is, by failing to form or adequately strengthen the new connections required to represent the overall plan for a sentence, H.M. made ''planning errors.'' For example, H.M. omitted the critical grammatical elements *it's* and *on* in an intended utterance resembling, ''he liked the new position because of it's being on a passenger line (see Example 2),'' because during initial planning, these elements were never adequately attached to a proposition-level representation. And because planning errors cannot be detected and corrected without forming and adequately strengthening the connections for semantic-level plans under NST (MacKay, 1992), H.M. failed to detect and correct his ''errors.'' Even the aprosodic character of H.M.'s speech production (Milner et al., 1968) fits a binding deficit hypothesis. Because prosodic cues signal what words link together to form phrases in sentences (see, e.g., Miller & MacKay, 1996), prosody is integral to sentence-level binding processes, and concomitant deficits in connection formation and prosody production make sense within NST. However, caution is in order here because H.M.'s monotonous and aprosodic speech could also stem from damage to his cerebellum, which has known relations to timing (e.g., Ivry & Keele, 1989), or from damage to his amygdala, which has known relations to emotional tone (Gray, 1982, p. 5).

We turn now to the issue of why proposition-level repetitions were so common in the ambiguity description task (Corkin, 1973) but virtually nonexistent in conversational speech (Marslen-Wilson, 1970). This difference seems related to the fact that H.M. had to reinterpret the same set of words in the ambiguity description task. Thus, under NST, H.M. was able to weakly represent the first meaning of the ambiguous sentences via fragile new connections, and was able to describe that meaning (with varying degrees of coherence) by activating the nodes representing the first meaning (see Figure 4), among others. However, forming the new connections required for inhibiting the dominant lexical node and for tagging his first-meaning description as ''already mentioned'' would be difficult for H.M., unlike controls. In addition, when H.M. described the first meaning, this would automatically strengthen his first-meaning connections via the engrainment learning process. As a result, when H.M. re-read the sentence in order to describe the second meaning, the (now more strongly connected) nodes for the first meaning would become activated again as the most primed nodes, and lacking an ''already mentioned'' tag, H.M. would repeat his first-meaning description once more. This second repetition would further strengthen connections for the first-meaning nodes and further increase their probability of activation instead of the second meaning nodes, so that H.M. would continue to retrieve and describe the first meaning as many times as the experimenter could tolerate (see Tables 2a,b,c).

The missing ''already mentioned'' tags may also have caused H.M. to redescribe his first meaning when he thought he was describing the second, and to describe the second meaning as if it were the first. This would explain three curious aspects of the Corkin transcript: H.M.'s frequent insistence that he had described two meanings when he had in fact only redescribed the first (see, e.g., H.M.'s ''I just gave you two'' in Table 2a); H.M.'s puzzlement when told that, despite repeated attempts, he had described only one meaning (see, e.g., H.M.'s ''The same meaning?'' in Table 2b);[7] and H.M.'s descriptions of the *sec*-

[7] Note that when H.M. learned that he had repeatedly expressed only one meaning in Table 2c, his response (''Yeh, in a way'') was neither puzzled nor contumacious.

*ond* meaning as being the first. For example, after repeating the first meaning eight times in Table 2b, H.M. described the second meaning as if it were the first: ‘‘Well, one would be to leave without hesitation.’’ Whether the increased sensitivity to retrieval interference that amnesics in general exhibit (Nadel, 1994; Warrington & Weiskrantz, 1974, 1978; see Shapiro & Olton, 1994; and Hayman, MacDonald, & Tulving, 1993, for reviews) reflects similar output interference processes is of course an open question. However, it is important to note that such retrieval interference would be absent in normal conversations, which flow from one topic to the next, without requiring reinterpretation of what has been said earlier, explaining the absence of proposition-level repetitions in H.M.’s conversational speech in the Marslen-Wilson transcript.

### *H.M. and Relations between Memory and Language Production*

Why should someone with a binding deficit or reduced ability to form new connections, experience problems in producing language? The answer is that forming new connections is integral to representing the new ideas for nonformulaic language production. This conclusion is consistent with other recent data indicating that language production and memory retrieval for verbal materials are inseparable, and that processes involved in everyday language production are also involved in verbal memory studies. An example is the tip-of-the-tongue (TOT) phenomenon, which typically occurs when speakers are unable to retrieve a familiar word such as *locust* or *Napoleon* during everyday speech production, even though they can often retrieve aspects of the word, e.g., its first letter, number of syllables, stress pattern, and other words similar in sound or meaning or both (see Burke et al., 1991). Semantic memory questions such as, ‘‘What do you call the leather band formerly used for sharpening an old-fashioned razor?’’ give exactly the same pattern of results as spontaneously occurring TOTs (see Burke et al., 1991), a case where ‘‘memory retrieval’’ and everyday speech production are indistinguishable. These and other examples (see Bock, 1996; MacKay & Abrams, 1996) where processes involved in language production are also involved in ‘‘memory retrieval’’ tasks are consistent with the observation that no one has been able to establish a dividing line, either empirically or theoretically, between where language production begins and where storage and retrieval of verbal materials ends.

*How general are H.M.’s memory-perception-production correlations?* It remains to determine whether H.M.’s semantic-level production deficit extends to other behaviors, but more than five other studies have already demonstrated links between hippocampal system involvement and various types of output planning in humans (Halgren, 1991) and other species: Wilson (1994, p. 499; see also Wilson, Riches, & Brown, 1990) noted close temporal relations between initiation of voluntary actions and electrophysiological activity in primate hippocampal cells, and reported that ‘‘hippocampal activity frequently predicted the intended goal of the hand’’ as it moved toward a target. Eichenbaum et al. (1994, p. 507) also observed that ‘‘most hippocampal cells fire closely time-locked to behavioral actions’’ (see also O’Mara, Rolls, Berthoz, & Kesner 1994; and Muller & Kubie, 1987). Close relations have also been observed between primate hippocampal activity and planned eye movements in complete darkness (Ringo, Sobotka, Diltz, & Bunce, 1994). Although Eichenbaum et al. (1994, p. 507) dismissed all of these data (including their own) as misleading and ‘‘simple correlations,’’ that should be ‘‘dissociated from the more ‘‘central’’ functions of the hippocampus,’’ these data make sense within NST because producing novel actions requires hippocampal binding functions. These many observations relat-

The contrast of this response with H.M.’s other responses is of interest because H.M. clearly only saw one meaning of this ambiguity, as indicated by his subsequent response: ‘‘Uh, I was thinking of the way he was cooking.’’ ‘‘Well, yes, I see. I know what you mean now on that one’’ (see Table 2c). Apparently, H.M. did not think he was describing the second meaning when repeatedly describing the first in this case.

ing output planning and hippocampal system activity also underscore the significance of H.M.'s semantic-level binding deficit in the characterisitcally human activity of producing speech.

A final generality issue is whether other amnesic patients with similar medial temporal lobe damage will show semantic-level production impairments resembling H.M.'s. The present research is not the first to note relations between deficits in long term episodic memory and language production (see Risse, Rubens, & Jordan, 1984), or between subcortical lesions and language production deficits (see, e.g., Alexander & Naeser, 1988; Metter, Riege, Hanson, Jackson, Kempler, & van Lanker, 1988), or between the processing of ambiguity and amnesia due to left hippocampal system damage (see Zaidel et al., 1995). Nor is the present study the first to suggest that children who suffer bilateral hippocampal damage very early in life will fail to acquire language in a normal manner (DeLong & Heinz, 1997; but see Vargha-Khadem, Gadian, Watkins, Connelly, Van Paesschen, & Mishkin, 1997).

*H.M., language, and memory tested directly versus indirectly.* Ogden and Corkin (1991) characterized dissociations between H.M.'s explicit versus implicit performance as the most robust generalization characterizing his memory impairment, and a pattern that H.M. shares with Korsakoff patients and people with amnesia from a wide variety of other causes: All exhibit sparing of implicitly tested memory in a variety of perceptual, motor, and cognitive tasks, despite inability to explicitly remember the tasks from one encounter to the next (see, e.g., Mayes, 1992; Shimamura, 1993). However, two observations call for qualification of this generalization based on the distinction between old versus new connections: H.M. only shows normal repetition priming for familiar words, and exhibits equivalent repetition priming for pronounceable nonwords and words introduced into English after his 1953 operation (Gabrieli et al., 1988).

Success on direct tests, e.g., recognition or recall that a specific stimulus word has been presented at a particular time, place, or context (e.g., in a particular list) depends on forming new connections at a relatively high level in the system to represent the link between the stimulus word and its time, place, or context of use (see the review of MacKay & Burke, 1990). Consequently, H.M. does poorly on direct tests because he has difficulty forming these new links between a word and its current episodic context. However, for indirect measures such as repetition priming, H.M. shows normal facilitative effects of presenting a familiar word on subsequent perception or production of the word because these facilitative effects involve well-established connections for perceiving and producing familiar words. These repetition priming effects result from engrainment learning, a process that does not require input from hippocampal binding nodes (MacKay, 1990), and is unimpaired in case H.M. Thus, if H.M. is shown the word COMPLIMENT, and is later given the stem COMPL and asked to produce the first word that comes to mind, he will tend to respond COMPLIMENT rather than, say, COMPLETION, because of his intact engrainment learning processes involving cortical connections that were formed during childhood for comprehending and producing the word COMPLIMENT. However, if H.M. is shown the word FRISBEE, and is later given the stem FRI, he will produce a familiar word, e.g., FRIDAY, rather than FRISBEE, because he lacks the connections for priming and producing this never-learned word.

Within this framework, data for normal controls performing direct and indirect tests further illustrate the identity of processes underlying everyday language comprehension and production on the one hand, and laboratory memory tasks on the other. For example, time required to begin production of a visually presented word (a ''language production task'') is reduced if participants have previously encountered the same word presented auditorily in noise (a ''language perception task'') or in a recognition memory task (a ''verbal memory task''). Such ''enhanced fluency through repetition'' is sometimes interpreted as the ''result of a newly created episodic representation of a word's occurrence'' (Masson & Freedman, 1990, p 355). However, a simpler hypothesis is that repetition-enhanced-fluency arises through strengthening of units and processes shared by language production (measured by onset time), language comprehension, and recognition memory tasks (see Bower, 1996, for a similar view), although different types of tasks can tap into these unitary language-memory abilities in different ways (for details, see MacKay & Abrams, 1996; MacKay & Burke, 1990).

### *H.M. and Relations between Language Comprehension and Production*

The fact that H.M. exhibits *comprehension deficits* that parallel his production deficits (see MacKay et al., 1997; also Table 5) raises two important theoretical questions: Why should someone with a general difficulty in forming new connections, experience parallel and concomitant problems in both the production and comprehension of language? The answer under NST is that forming new connections is integral to representing new ideas for producing and comprehending nonformulaic language, and a single set of binding nodes within the hippocampal system binds together ''common cortical units'' that play a role in both the production and comprehension of language (see MacKay 1990, 1987, p. 6).

Consistent with this ''common components'' hypothesis, microelectrode stimulation at one and the same cortical site affects both production and perception of corresponding phonological units, suggesting that units for production and perception are neurally inseparable at phonological levels (see Ojemann, 1983; also the neuroimaging data of Kempler, Curtiss, Metter, Jackson, & Hanson, 1991). Further, a variety of experimental data make theoretical sense if common cortical components underlie perception and production at semantic as well as phonological levels (see MacKay, 1987, pp. 14–194). These common component data include a wide range of parallel empirical effects in production and perception, interactions between processes for production vs. perception, units in perception and production, the nature of errors in perception and production, bottom-up effects in production, and top-down effects in perception. Support for common perception-production components also comes from verbal transformation effects (MacKay, Wulf, Yin, & Abrams, 1993), and from a growing set of non-language tasks (see, e.g., Muessler & Hommel, 1996; also Prinz, 1990, 1992 for reviews).

What then of alleged support for entirely separate comprehension and production components, i.e., occurrence of comprehension disorders (e.g., Wernicke's aphasia) without concomitant production disorders (e.g., Broca's aphasia), and vice versa? Here too, more recent findings from a variety of new and highly sophisticated techniques suggest that aphasias are more complicated than originally thought: With appropriate controls for lesion size, as well as for pragmatic (non-linguistic) aids to comprehension, Wernicke's and Broca's aphasics exhibit both receptive and expressive deficits that tend to be commensurate in nature and in extent (for reviews, see MacKay, 1987, p. 5, and Kempler et al., 1991). For example, lesions in Broca's area result in both production aphasia *and* perceptual deficits (Blumstein, Baker, & Goodglass, 1977). In short, H.M.'s concomitant comprehension and production deficits are consistent with many different types of neurological data, including the original type of data once thought to support the separation of comprehension and production.

However, H.M.'s concomitant comprehension and production deficits raise a difficult question for stages-of-processing theories: How can H.M.'s relatively restricted subcortical lesion simultaneously cause related deficits in both language comprehension and language production, supposedly autonomous stages that occupy opposite ends of the stage-of-processing spectrum (see Figure 1)? Many other findings raise parallel questions regarding the assumed autonomy of language comprehension and production in stages-of-processing theories, e.g., the virtually identical effects of word frequency on lexical decision times, once considered a ‘‘pure comprehension measure’’, and picture naming times, once considered a ‘‘pure production measure’’ (see Bock, 1996).

### *Caveats and Limitations*

Several caveats regarding the present results and hypotheses are in order. One concerns the functioning of H.M.’s posterior hippocampus: If thousands of binding nodes are specialized for conjoining different classes of never previously linked units for the normal production and acquisition of language (at all ages; MacKay, 1990), and if H.M.’s posterior hippocampus is functionally intact (see Corkin et al, 1997), then some of H.M.’s language-specific binding nodes have been spared, but we cannot be certain how many or which language-specific binding nodes have been destroyed or spared in H.M. Similar caveats regarding H.M.’s damaged versus intact binding nodes also apply to impaired versus residual capacities in areas such as motor learning (Corkin, 1968). However, it is also possible that H.M.’s normal improvement with practice on a variety of tests of motor ability (see, e.g., Corkin, 1984) is the result of engrainment learning processes rather than new connection formation.

A second class of caveats concerns impairment outside H.M.’s hippocampal system. Because patients with nonoperated left temporal lobe epilepsy exhibit word retrieval difficulties independent of overt seizures (Mayeux, Brandt, Rosen, & Benson, 1980), residual epilepsy may be the cause of H.M.’s word retrieval difficulties. It is also possible that H.M.’s cerebellar damage or the extremely small lesions at the tips of H.M.’s temporal poles (Corkin et al., 1997) affected his language production: Recent data indicate that language production engages many areas of the brain once considered unrelated to language (see, e.g., Poeppel, 1996). Disuse may also have contributed to H.M.’s production deficits, and especially his word retrieval difficulties. For example, H.M.’s verbal skills may have received less than normal exercise due to blunting of his experience by epilepsy-controlling drugs.

Finally, we wish to stress the limitations of our claim that language and memory for verbal materials cannot be completely separated, and that H.M.’s binding deficit contributes simultaneously to his production deficits and his memory deficits involving verbal materials. We are not arguing that H.M.’s memory deficits are due to his production deficits or that his production deficits are due to his memory deficits: These are stages-of-processing arguments. We also wish to stress that our data do not rule out basic mechanisms postulated in other distributed-memory accounts of hippocampal system amnesia (e.g., Carpenter & Grossberg, 1993; Grafman & Weingartner, 1996; McClelland, 1985; Metcalfe et al., 1992; Wickelgren, 1979; Woolf, 1996). However, our data do challenge these theories to address language production and its relation to other distributed-memory functions such as language comprehension in order to fully account for H.M.’s deficits.

### *Why Were H.M.’s Language Production Deficits so Difficult to Detect?*

Our observed differences between H.M. and memory-normal controls raise one final question: How could so many previous studies fail to detect H.M.’s language production deficits? Many early studies lacked normal controls, and lacked detailed verbatim transcripts needed for analyzing output characteristics such as focus, grammaticality, and comprehensibility, and for averting the unconscious conceptual repairs that sophisticated listeners readily introduce when interpreting defective output. H.M.’s normal verbal IQ may also have encouraged previous researchers to overlook or de-emphasize his independent difficulties in creating and expressing new sentence-level meanings. Previous researchers may also have considered H.M.’s subtle production deficits relatively trivial and not worth mentioning in comparison with his other debilitating problems (see Milner et al., 1968), or in comparison with the massive production deficits of aphasics. For example, unlike aphasics, H.M. does not generate agrammatic word salads, placing a subject after a verb in an assertive proposition, or an adjective after a noun in a noun phrase. In short, H.M.'s intact abilities to repeat and to use words and phrases acquired before his operation may have masked his somewhat subtle deficits with novel aspects of language use. As a consequence, researchers may have overlooked problems that would suggest impairment in otherwise normal individuals, a process that the generally accepted stages-theory of language may have facilitated. The stages-of-processing framework may also have encouraged ''pure memory'' interpretations of behaviors with other possible explanations. An example is the observation that H.M. never wrote notes to himself as reminders, even though he repeatedly complained of his difficulties in remembering (see Sidman et al., 1968). The stages-of-processing framework suggested that such notes were not worth the trouble because H.M. would forget to use them. However, it is equally possible that H.M.'s language production deficits made such notes difficult to create in the first place.

## REFERENCES

Abrams, L., Dyer, J. R., & MacKay, D. G. (1996). Repetition blindness interacts with syntactic grouping in rapidly presented sentences. *Psychological Science,* **7,** 100–104.

Alexander, M. P., & Naeser, M. A. (1988). Cortical-subcortical differences in aphasia. In F. Plum (Ed.), *Language, communication and the brain* (pp. 215–228). New York: Raven Press.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence, & J. T. Spence (Eds.), *The Psychology of learning and motivation: Advances in research and theory vol. 2* (pp. 89–195). New York: Academic Press.

Arbuckle, T. Y., & Gold, D. P. (1993). Aging, inhibition, and verbosity. *Journal of Gerontology: Psychological Sciences,* **48,** P225–P232.

Baddeley, A., & Hitch, G. J. (1974). Working memory. In G.H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47–90). New York: Academic Press.

Blumstein, S. E., Baker, E., & Goodglass, H. (1977). Phonological factors in auditory comprehension in aphasia. *Neuropsycholgia,* **15,** 19–30.

Bock, K. (1996). Language production: Methods and methodologies. *Psychonomic Bulletin & Review,* **3,** 395–421.

Bower, G. H. (1996). Reactivating a reactivation theory of implicit memory. *Consciousness and Cognition,* **5,** 27–73.

Broca, P. (1865). Sur la faculté du langage articulé. *Bulletin of Social Anthropology,* **4,** 493–4.

Burke, D. M., MacKay, D. G., Worthley, J. S., & Wade, E. (1991). On the tip of the tongue: What causes word finding failures in young and older adults? *Journal of Memory and Language,* **30,** 542–579.

Caplan, D., & Waters, G. S. (1990). Short-term memory and language comprehension: A critical review of the psychological literature. In G. Vallar, & T. Shallice (Eds.), *Neuropsychological impairments of short-term memory* (pp. 337–389). Cambridge: Cambridge University Press.

Carpenter, G., & Grossberg, S. (1993). Normal and amnesic learning, recognition, and memory by a neural model of cortico-hippocampal interactions. *Trends in the Neurosciences,* **16,** 131–37.

Cohen, N., & Eichenbaum, H. B. (1993). *Memory, amnesia, and the hippocampal system.* Cambridge, MA: MIT Press.

Corkin, S. (1968). Acquisition of motor skill after bilateral medial temporal-lobe excision. *Neuropsychologia,* **6,** 255–265.

Corkin, S. (July, 1973). *H.M.'s comprehension and description of ambiguous meanings.* Unpublished transcript, Dept. of Brain and Cognitive Sciences, M.I.T., Cambridge, MA.

Corkin, S. (1984). Lasting consequences of bilateral medial temporal lobectomy: Clinical course and experimental findings in H.M. *Seminars in Neurology,* **4,** 249–259.

Corkin, S., Amaral, D. G., González, R. G., Johnson, K. A., & Hyman, B. T. (1997). H.M.'s medial temporal lobe lesion: Findings from MRI. *Journal of Neuroscience,* **17,** 3964–3979.

Corsi, P. M. (1972). *Human memory and medial temporal regions of the brain.* Unpublished PhD. thesis, McGill University, Montreal.

Dell, G. (1986). A spreading activation theory of retrieval in sentence production. *Psychological Review,* **93,** 283–321.

DeLong, G. R., & Heinz, E. R. (1997). The clinical syndrome of early-life bilateral hippocampal sclerosis. *Annals of Neurology,* **42,** 11–17.

Drachman, D. A., & Arbit, J. (1966). Memory and the hippocampal complex II. Is memory a multiple process? *Archives of Neurology,* **15,** 52–61.

Eichenbaum, H. B., Otto, T., & Cohen, N. (1994). Two functional components of the hippocampal memory system. *Behavioral & Brain Sciences,* **17,** 449–518.

Freed, D. M., & Corkin, S. (1988). Rate of forgetting in H.M.: 6-month recognition. *Behavioral Neurology,* **102,** 823–827.

Freed, D. M., Corkin, S., & Cohen, N. J. (1987). Forgetting in H.M.: A second look. *Neuropsycholgia,* **25,** 461–471.

Gabrieli, J. D. E., Cohen, N. J., & Corkin, S. (1988). The impaired learning of semantic knowledge following bilateral medial temporal-lobe resection. *Brain & Cognition,* **7,** 157–177.

Gathercole, S. E., & Baddeley, A. D. (1993). *Working memory and language.* Hillsdale, NJ: Erlbaum.

Garrett, M. F. (1988). Processes in language production. In F.J. Newmeyer (Ed.), *Linguistics: The Cambridge Survey, III. Language: Psychological and biological aspects* (pp. 69–96). Cambridge: Cambridge University Press.

Gordon, W. C. (1989). *Learning and memory.* Pacific Grove, CA: Brooks/Cole.

Graf, P., & Schachter, D. (1985). Implicit and explicit memory for new associations in normal and amnesic subjects. *Journal of Experimental Psychology: Learning, Memory & Cognition,* **11,** 501–518.

Grafman, J., & Weingartner, H. A. (1996). A Combinatorial-Binding and Strength (CBS) model of memory: Is it a better framework for amnesia? In D. Herrmann, M. Johnson, C. McEvoy, C. Hertzog, & P. Hertel (Eds.), *Basic and applied memory: Theory in context* (259–276). Hillsdale, N.J.: Lawrence Erlbaum Associates.

Gray, J. A. (1982). *The neuropsychology of anxiety: An enquiry into the functions of the septo-hippocampal system* (pp. 1–548). New York: Oxford University Press.

Haglund, K., & Collett, C. (1996). Found memories: Patient H.M.: The Landmarks Interviews. *The Journal of NIH Research,* **8,** 42–50.

Halgren, E. (1991). Firing of human hippocampal units in relation to voluntary movements. *Hippocampus,* **1,** 153–162.

Hayman, C. A. G., MacDonald, C. A., & Tulving, E. (1993). The role of repetition and associative interference in new semantic learning in amnesia. *Journal of Cognitive Neuroscience,* **5,** 375–389.

Hebben, N., Corkin, S., Eichenbaum, H., & Shedlack, K. (1985). Diminished ability to interpret and report internal states after bilateral medial temporal resection: Case H.M. *Behavioral Neuroscience,* **99,** 1031–1039.

Hilts, P. J. (1995). *Memory's ghost: The strange tale of Mr. M. and the nature of memory.* New York: Simon & Schuster.

Ivry, R. B., & Keele, S. W. (1989). Timing functions of the cerebellum. *Journal of Cognitive Neuroscience,* **1,** 136–152.

Jones-Gotman, M. (1987). Commentary: Psychological evaluation—Testing hippocampal function. In J. Engel Jr. (Ed.), *Surgical treatment of the epilepsies* (pp. 203–211). New York: Raven Press.

Keane, M. M., Gabrieli, J. D. E., & Corkin, S. (1987). Multiple relations between fact-learning and priming in global amnesia. *Society for Neuroscience Abstracts,* **13,** 1454.

Keane, M. M., Gabrieli, J. D. E., Mapstone, H. C., Johnson, K. A., & Corkin, S. (1995). Double dissociation of memory capacities after bilateral occipital-lobe or medial temporal-lobe lesions. *Brain,* **118,** 1129–1148.

Kempen, G., & Hoencamp, E. (1987). An incremental procedural grammar for sentence formulation. *Cognitive Science,* **11,** 201–258.

Kempler, D., Curtiss, S., Metter, E. J., Jackson, C. A., & Hanson, W. R. (1991). Grammatical comprehension, aphasic syndromes, and neuroimaging. *Journal of Neurolinguistics,* **6,** 301–318.

Kesner, R. P. (1985). Correspondence between humans and animals in coding of temporal attributes: Role of hippocampus and prefrontal cortex. In D.S. Olton, E. Gamzu, & S. Corkin (Eds.), *Memory dysfunctions: An integration of animal and human research from preclinical and clinical perspectives* (vol. 444, pp. 122–136). New York: New York Academy of Sciences.

Kintsch, W., Welsch, D., Schmalhofer, F., & Zimny, S. (1990). Sentence memory: A theoretical analysis. *Journal of Memory and Language,* **29,** 133–159.

Kolb, B., & Whishaw, I. (1996). *Fundamentals of human neuropsychology,* 4th ed. New York: W.H. Freeman & Co.

Lackner, J. R. (1974). Observations on the speech processing capabilities of an amnesic patient: Several aspects of H.M.'s language function. *Neuropsychologia,* **12,** 199–207.

Levelt, W. J. M. (1989). *Speaking: From intention to articulation.* Cambridge, MA: MIT Press.

Lombardi, L., & Potter, M. C. (1992). The regeneration of syntax in short-term memory. *Journal of Memory & Language,* **31,** 713–733.

MacKay, D. G. (1982). The problems of flexibility, fluency, and speed-accuracy trade-off in skilled behavior. *Psychological Review,* **89,** 483–506.

MacKay, D. G. (1987). *The organization of perception and action: A theory for language and other cognitive skills.* New York: Springer-Verlag.

MacKay, D. G. (1990). Perception, action, and awareness: A three-body problem. In O. Neumann, & W. Prinz (Eds.), *Relationships between perception and action* (pp. 269–303). Berlin: Springer-Verlag.

MacKay, D. G. (1992). Awareness and error detection: New theories and paradigms. *Consciousness and Cognition,* **1,** 199–225.

MacKay, D. G. (1997). The stages of processing metatheory and relations between perception, action, and memory. In W. Bechtel, & G. Graham (Eds.), *A Companion to Cognitive Science.* Oxford: Blackwell, in press.

MacKay, D. G., & Abrams, L. (1994, November). *Chunking and repetition deficits challenge capacity theories and the single attachment principle.* Paper presented at the 35th annual meeting of the Psychonomic Society, St. Louis.

MacKay, D. G., & Abrams, L. (1996). Language, memory, and aging: Distributed deficits and the structure of new-versus-old connections. In J. E. Birren, & W. K. Schaie (Eds.), *Handbook of the psychology of aging, 4th ed.* (pp. 251–265). San Diego: Academic Press.

MacKay, D. G., & Bever, T. G. (1967). In search of ambiguity. *Perception & Psychophysics,* **2,** 193–200.

MacKay, D. G., & Burke, D. M. (1990). Cognition and aging: A theory of new learning and the use of old connections. In T. Hess (Ed.), *Aging and cognition: Knowledge organization and utilization* (pp. 281–300). Amsterdam: North-Holland.

MacKay, D. G., & Miller, M. D. (1996a). Is connectionism the final stage of information processing? A review of ''The Structure of Long-Term Memory: A Connectivity Model of Semantic Processing.'' By Wolfgang Klimesch. *American Journal of Psychology,* **109,** 162–171.

MacKay, D. G., & Miller, M. D. (1996b). Can cognitive aging contribute to fundamental psychological theory? Repetition deafness as a test case. *Aging, Neuropsychology, & Cognition,* **3,** 169–186.

MacKay, D. G., Miller, M. D., & Schuster, S. P. (1994). Repetition blindness and aging: Evidence for a binding deficit involving a single, theoretically specified connection. *Psychology & Aging,* **9,** 251–258.

MacKay, D. G., Stewart, R., & Burke, D. M. (in press). H.M. revisited: Relations between language comprehension, memory, and the hippocampal system. *Journal of Cognitive Neuroscience.*

Marslen-Wilson, W. (1970). *Biographical interviews with H.M.* Unpublished transcript (pp. 1–144). Referenced in Marslen-Wilson & Teuber (1975).

Marslen-Wilson, W., & Teuber, H-L. (1975). Memory for remote events in anterograde amnesia: Recognition of public figures from news photographs. *Neuropsychologia,* **13,** 353–364.

Massaro, D. W. (1994). Introducing information processing: 25 years later. *American Journal of Psychology,* **107,** 597–641.

Masson, M. E. J., & Freedman, L. (1990). Fluent identification of repeated words. *Journal of Experimental Psychology: Learning, Memory, & Cognition,* **16,** 355–373.

Mayes, A. (1992). Brain damage and memory disorders. In M. Gruneberg, & P. Morris (Eds.), *Aspects of memory* (pp. 86–123). London: Routledge.

Mayeux, R., Brandt, J., Rosen, J., & Benson, F. (1980). Interictal memory and language impairment in temporal lobe epilepsy. *Neurology,* **30,** 120–125.

McClelland, J. L. (1985). Distributed models of cognitive processes: Applications to learning and memory. In D.S. Olton, E. Gamzu, & S. Corkin (Eds.), *Memory dysfunctions: An integration of animal and human research from preclinical and clinical perspectives* (vol. 444, pp. 1–9). New York: New York Academy of Sciences.

McClelland, J. L., McNaughton, B. L., & O'Reilly, R. C. (1995). Why are there complementary learning systems in the hippocampus and neocortex: Insights from the success and failures of connectionist models of learning and memory. *Psychological Review,* **102,** 419–457.

Metcalfe, J., Cottrell, G. W., & Mencl, W. E. (1992). Cognitive binding: A computational-modeling analysis of a distinction between implicit and explicit memory. *Journal of Cognitive Neuroscience,* **4,** 289–298.

Metter, E. J., Riege, W. H., Hanson, W. R., Jackson, C. A., Kempler, D., & van Lanker, D. (1988). Subcortical structures in aphasia: An analysis based on (F-18)-fluorodeoxyglucose, positron emission tomography, and computed tomography. *Archives of Neurology,* 45, 1229–1234.

Miller, M. D., & MacKay, D. G. (1996). Relations between language and memory: The case of repetition deafness. *Psychological Science,* **7,** 347–351.

Milner, B. (1963). Effects of different brain lesions on card sorting. *Archives of Neurology,* **9,** 90–100.

Milner, B. (1975). Psychological aspects of focal epilepsy and its neurosurgical management. In D. P. Purpura, J. K. Penny, & R. D. Walter (Eds.), *Advances in neurology, Vol. 8* (299–320). New York: Raven Press.

Milner, B., Corkin, S., & Teuber, H. L. (1968). Further analysis of the hippocampal amnesic syndrome: 14-year follow-up study of H. M. *Neuropsychologia,* **6,** 215–234.

Muller, R. U., & Kubie, J. L. (1987). The firing of hippocampal place cells predicts the future position of freely moving rats. *Journal of Neuroscience,* **9,** 4101–10.

Muter, P. (1980). Very rapid forgetting. *Memory & Cognition,* **8,** 174–179.

Nadel, L. (1994). Multiple memory systems: What and why; an update. In D.L. Schachter, & E. Tulving (Eds.), *Memory systems 1994* (pp. 39–63). Cambridge, MA: MIT Press.

Ogden, J. A., & Corkin, S. (1991). Memories of H.M. In W. C. Abraham, M. Corballis, & K. G. White (Eds.), *Memory mechanisms: A tribute to G. V. Goddard* (pp. 195–215). Hillsdale, NJ: Erlbaum.

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map.* Oxford: Clarendon Press.

O'Mara, S. M., Rolls, E. T., Berthoz, A., & Kesner, R. P. (1994). Neurons responding to whole-body motion in the primate hippocampus. *Journal of Neuroscience,* **14,** 6511–6523.

Pashler, H., & Carrier, M. (1996). Structures, processes, and the flow of information. In E. L. Bjork, & R. A. Bjork (Eds.), *Memory* (pp. 4–29). San Diego: Academic Press.

Poeppel, D. (1996). A critical review of PET studies of phonological processing. *Brain and Language,* **55,** 317–351.

Price, C., Wise, R., Watson, J., Petterson, K., Howard, D., & Franckowiak, R. (1994). Brain activity during reading: the effects of exposure duration and task. *Brain,* **117,** 1255–1269.

Rempel-Clower, N. L., Zola, S. M., Squire, L. R., & Amaral, D. G. (1996). Three cases of enduring memory impairment after bilateral damage limited to the hippocampal formation. *Journal of Neuroscience,* **16,** 5233–5255.

Ringo, J. L., Sobotka, S., Diltz, M. D., & Bunce, M. C. (1994). Eye movements modulate activity in hippocampal, parahippocampal, and inferotemporal neurons. *Journal of Neurophysiology,* **71,** 1285–88.

Risse, G. L., Rubens, A. B., & Jordan, L. S. (1984). Disturbances of long-term memory in aphasic patients. *Brain,* **107,** 605–617.

Saffran, E. M. (1990). Short-term memory impairment and language processing. In A. Caramazza (Ed.), *Cognitive neuropsychology and neurolinguistics: Advances in models of cognitive function and impairment* (pp. 137–168). Hillsdale, NJ: Erlbaum.

Sagar, H. J., Cohen, N. J., Corkin, S., & Growdon, J. H. (1988). Dissociations among processes in remote memory. In D.S. Olton, E. Gamzu, & S. Corkin (Eds.), *Memory dysfunctions: An integration of animal and human research from preclinical and clinical perspectives. Annals of the New York Academy of Sciences* (Vol. 444, pp. 533–535). New York: New York Academy of Sciences.

Schachter, D. L. (1990). Perceptual representation systems and implicit memory: Toward a resolution of the multiple memory systems debate. In A. Diamond, (Ed.), *Development and neural basis of higher cognitive functions* (pp. 543–571). Annals of the New York Academy of Sciences. New York: New York Academy of Sciences.

Schweickert, R., & Boruff, B. (1986). Short-term memory capacity: Magic number or magic spell? *Journal of Experimental Psychology: Learning, Memory, & Cognition,* **12,** 419–425.

Scoville, W. B. (1968). Amnesia after bilateral mesial temporal-lobe excision: Introduction to case H.M. *Neuropsychologia,* **6,** 211–213.

Scoville, W. B., & Milner, B. (1957). Loss of recent memory after bilateral hippocampal lesions. *Journal of Neurology, Neurosurgery, and Psychiatry,* **20,** 11–21.

Shanks, D. (1996). *Learning and memory.* In D.W. Green and others (Eds.), *Cognitive science: An introduction* (pp. 276–309). Oxford: Blackwell.

Shimamura, A. P. (1993). Neuropsychological analyses of implicit memory: History, methodology, and theoretical interpretations. In P. Graf, & M. E. J. Masson (Eds.), *Implicit memory: New directions in cognition, development, and neuropsychology* (pp.265–285). Hillsdale, NJ: Lawrence Erlbaum.

Shapiro, M. L., & Olton, D. S. (1994). Hippocampal function and interference. In D.L. Schachter, & E. Tulving (Eds.), *Memory systems 1994* (pp. 87–117). Cambridge, MA: MIT Press.

Sidman, M. Stoddard, R. T., & Mohr, J. P. (1968). Some additional quantitative observations of immediate memory in a patient with bilateral hippocampal lesions. *Neuropsychologia,* **6,** 245–254.

Squire, L. R. (1987). *Memory and brain.* New York: Oxford University Press.

Tulving, E. (1983). *Elements of episodic memory.* Oxford: Clarendon Press.

Vallar, G., & Baddeley, A. D. (1984). Fractionation of working memory: Neuropsychological evidence for a short-term store. *Journal of Verbal Learning and Verbal Behavior,* **23,** 151–161.

Van Riper, C. (1982). *The nature of stuttering.* Englewood Cliffs, NJ: Prentice-Hall.

Vargha-Khadem, F., Gadian, D. G., Watkins, K. E., Connelly, A., Van Paesschen, W., & Mishkin, M. (1997). Differential effects of early hippocampal pathology on episodic and semantic memory. *Science,* **277,** 376–380.

Warrington, E. K., & Weiskrantz, L. (1974). The effect of prior learning on subsequent retention in amnesic patients. *Neuropsychologia,* **12,** 419–428.

Warrington, E. K., & Weiskrantz, L. (1978). Further analysis of the prior learning effect in amnesic patients. *Neuropsychologia,* **16,** 169–177.

Wickelgren, W. A. (1968). Sparing of short-term memory in an amnesic patient: Implications for strength theory of memory. *Neuropsychologia,* **6,** 235–244.

Wickelgren, W. A. (1975). The long and the short of memory. In D. Deutsch, & J. A. Deutsch (Eds.), *Short-term memory* (pp. 41–63). New York: Academic Press.

Wickelgren, W. A. (1979). Chunking and consolidation: A theoretical synthesis of semantic networks, configuring in conditioning, S-R versus cognitive learning, normal forgetting, the amnesic syndrome and the hippocampus arousal system. *Psychological Review,* **86,** 44–60.

Wilson, F. A. (1994). Hippocampal neuronal activity in rat and primate: Memory and movement. *Behavioral & Brain Sciences,* **17,** 499–500.

Wilson, F. A., Riches, I. P., & Brown, M. W. (1990). Hippocampus and medial temporal cortex: Neuronal activity related to behavioral responses during performance of memory tasks by primates. *Behavioral & Brain Research,* **40,** 7–28.

Woolf, N. J. (1996). Global and serial neurons form a hierarchically arranged interface proposed to underlie memory and cognition. *Neuroscience,* **74,** 625–651.

Zaidel, D. W., Zaidel, E., Oxbury, S. M., & Oxbury, J. M. (1995). The interpretation of sentence ambiguity in patients with unilateral focal brain surgery. *Brain and Language,* **51,** 458–468.

(Received March 3, 1997)
(Revision received August 22, 1997)