Strategic Processing and Memory for Temporal Order in Patients With Fronto Lobe Lesions

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This study evaluated whether deficits in memory for temporal order in patients with frontal lobe lesions result from impaired automatic encoding of temporal information or are secondary to deficits in effortful processes, such as the use of organizational strategies and control of interference. Participants were tested on temporal order reconstruction of semantically related and unrelated word lists learned under intentional or incidental conditions. Memory for temporal order in patients with frontal lobe lesions was sensitive to semantic relatedness but not to intention to learn. Tests of item free recall and recognition using similar encoding manipulations indicated that order performance in these patients was dissociable from item memory. Results indicate that automatic processing of temporal information is intact in patients with frontal lobe lesions but that strategic processing of this information is impaired.

These findings suggest that temporal order deficits are a fundamental aspect of frontal lobe dysfunction. Nonetheless, the underlying mechanism responsible for these deficits is not well understood. Hasher and Zacks (1979) originally characterized temporal encoding as a unitary and automatic process requiring minimal demand on attentional capacity. However, more recent studies indicate that tests of temporal order draw on multiple encoding and retrieval processes. Although some processes involved in the initial encoding of temporal information might be automatic, significant effects of practice, intelligence, strategy, and attention at encoding on memory for temporal order indicate that these initial temporal codes can be augmented by effortful processing (e.g., Jackson, 1990; Naveh-Benjamin, 1990; Zacks et al., 1984). Otherwise, whether the frontal lobes are involved in all or only some of these processes.

Some researchers have proposed that the frontal lobes are mainly responsible for the automatic encoding of spatiotemporal information (Milner et al., 1991; Milner, Petrides, & Smith, 1985; Schacter, 1987). For example, Schacter proposed that the frontal lobes were responsible for “contextual chunking,” a process hypothesized to be both automatic and necessary for segmenting information into discrete, temporally distinctive units (Pribram & Tubbs, 1967). Others, however, have emphasized the importance of the frontal lobes in functions related to the central executive in working memory (e.g., Baddeley, 1986; Norman & Shallice, 1986; Stuss & Benson, 1986). Executive function is generally associated with effortful processes, such as the ability to select task-relevant information and inhibit irrelevant information, as well as the ability to form and maintain strategies to organize what is encoded, retrieved, or both (Baddeley, 1986; Hasher & Zacks, 1988; also see Norman & Shallice, 1986; Zacks & Hasher, 1994). According to this view, impaired temporal order performance in patients with frontal lobe lesions exhibit deficits on tasks requiring encoding and retrieval of temporal information, such as recency discrimination (Butters, Kasznia, Glisky, Eslinger, & Schacter, 1994; Kesner, Hopkins, & Fineman, 1994; McAndrews & Milner, 1991; Milner, Corsi, & Leonard, 1991) and serial order reconstructions are evidence of the artistic and computer talents of Clay Clayworth.

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lobe lesions may not result from primary deficits in automatic processing of temporal information, but may be secondary to impaired central executive processes that limit their ability to organize further what has been encoded automatically.

Thus far, few researchers have examined the relationship between strategic processes and memory for temporal information in patients with frontal lobe lesions (Butters et al., 1994; McAndrews & Milner, 1991). The majority of the researchers have examined how order memory in patients with frontal lobe lesions is affected by subject-performed tasks (SPTs), a relatively noneffortful, nonstrategic encoding manipulation in which participants perform a meaningful action with the to-be-remembered item (e.g., squeezing the sponge; Cohen, 1981; Engelkamp & Zimmer, 1989; Nilsson & Cohen, 1988). When items were encoded using SPTs, patients with frontal lobe lesions performed comparably to control individuals on recency discrimination. However, other encoding techniques, such as imagining the movement, watching the experimenter perform the movement, or verbal elaboration, did not improve patients' performance (Butters et al., 1994). These other encoding techniques are generally considered to require more attentional effort than SPTs. Thus, compensation of temporal order deficits in patients with frontal lobe lesions may be possible only through encoding methods that do not require effortful, self-initiated strategies.

These findings suggest that temporal order deficits in patients with frontal lobe lesions are linked to deficits in controlled processes at encoding. However, this issue has not been addressed using nonmanipulated items. I investigated the relationship between memory for temporal order and executive function by manipulating intention to learn and the potential for semantic interference in a standard verbal learning paradigm. As such, I attempted to assess directly whether patients with frontal lobe lesions have a primary deficit in the automatic encoding of temporal information or whether order deficits are secondary to impaired control processes, such as the use of organizational strategies and control of interference.

I evaluated the role of strategic processing in memory for temporal order by manipulating intention to learn. At study, participants were either fully informed of the upcoming memory test (i.e., intentional learning) or simply performed an orienting task, such as pleasantness or size judgments (i.e., incidental learning). Under intentional learning conditions, it is likely that control individuals will use strategies to enhance their performance, given that they appear to do so in other tasks such as item free recall (e.g., Eslinger & Grattan, 1994; Gershberg & Shimamura, 1995; Stuss, Alexander, et al., 1994). Under incidental learning conditions, however, neither group should use organizational encoding strategies because there is no expectation of an upcoming test. Thus, if patients with frontal lobe lesions are impaired on tests of temporal order because they fail to use organizational strategies, group differences should be largest under intentional learning conditions but reduced or eliminated when items are learned incidentally.

I examined the relationship between inhibitory control and memory for temporal order by manipulating the degree of semantic interference in the study list. Specifically, under both encoding conditions, participants studied lists in which each item was a member of a different category (unrelated list) or was a member of one of four categories (related list). It is well established that semantic similarity impairs performance on tests of serial recall or order reconstruction (e.g., Crowder, 1979; Murdock, 1976; Nairne, 1990; Serra & Nairne, 1993). In long-term memory, this disruptive effect has been attributed to the interference between activation of semantic interitem associations and memory for episodic, serial associations (Nairne, 1990; Serra & Nairne, 1993). Given that frontal lobe damage may increase sensitivity to semantic interitem interference, as illustrated on tests of part-list cuing (Incisa della Rocchetta & Milner, 1993) and AB-AC paired-associates learning (Shimamura, Jurica, Mangels, Gershberg, & Knight, 1995), the order memory of patients with frontal lobe lesions may be disproportionately impaired by the semantic interference present in the related list.

Order reconstruction of the related list also may reveal strategic processing deficits in these patients. Although organizational strategies impart a general benefit to order memory (Jackson, 1990; Naveh-Benjamin, 1990; Zacks et al., 1984), they may be particularly critical when semantic interference is present (Poirier & Saint-Aubin, 1995). For example, strategies that link together adjacent items in an elaborative manner, such as relating them in a sentence or story, would strengthen serial associations against the disrupting effects of semantic interference. Thus, the negative effects of semantic similarity on order memory may be exacerbated in patients with frontal lobe lesions if they are less effective at using these elaborative strategies.

To summarize the predictions for this study, if order deficits in patients with frontal lobe lesions are secondary to deficits in strategic processing and inhibitory control, order performance should be strongly influenced by both intention to learn and the nature of the materials to be learned. By contrast, if lesions in dorsolateral prefrontal cortex impair fundamental components of temporal encoding, such as the ability to segment information into temporally discrete units, these patients should demonstrate impaired memory for temporal order across all item and instructional manipulations.

Although the focus of this study was memory for temporal information, I also assessed item free recall and recognition using similar materials and task manipulations. Item free recall was included to provide information about strategic processing in a retrieval task that does not explicitly require order information. Specifically, in both temporal order reconstruction and item free recall, strategic organization at retrieval was assessed using measures of serial association and semantic clustering. By comparing strategic processing across these tasks, it may be possible to determine whether organization used in temporal retrieval tasks is related to or dissociable from that used in nontemporal tasks. Finally, as in previous tests of temporal order (e.g., Kesner et al., 1994; Milner et al., 1991; Shimamura et al., 1990), I included an item recognition task to evaluate
whether order memory was related to memory for the items themselves.

Method

Incidental and intentional temporal order and item memory tests were administered and analyzed in four experiments. However, given the similar methodology of the four experiments, they are described together.

Participants

Patients With Frontal Lobe Lesions

Six patients with unilateral frontal lobe lesions were identified by review of medical records and computed tomography (CT) and magnetic resonance (MR) images. Figure 1 shows reconstructions of individual patient lesions based on CT scans and MR images. This figure includes a composite reconstruction illustrating that the area of greatest lesion overlap was in the midlateral and posterior regions of the dorsolateral prefrontal cortex. Lesions resulted from a single cerebral infarct in the territory of the precentral branch of the middle cerebral artery. Four patients had left hemisphere lesions (3 men and 1 woman), and 2 patients had right hemisphere lesions (1 man and 1 woman). Average lesion volume was estimated from quantitative analyses of neuroimaging data to be 29.7 cm³. Patients had no known history of other significant medical disease such as psychiatric disorder, dementia, substance abuse, or additional neurological events (e.g., head injury). The patients averaged 67.5 years of age (range = 62–76) and had an average of 13.8 years of education (see Table 1). For all patients, the cerebrovascular accident (CVA) occurred between 1980 and 1989, with an average of 10.5 years between CVA and current testing.

On tests of general intellectual and memory functioning (see Table 1), patients scored within the normal range. On the Wechsler Adult Intelligence Scale—Revised (WAIS-R; norm = 100), they had an average Full Scale score of 101.7 and a Verbal Scale score of 97.33. Their mean scores on the five scales of the Wechsler Memory Scale—Revised (WMS-R; norm = 100) were as follows: Attention = 94.5, General Memory = 97.5, Delayed Memory = 87.0, Verbal Memory = 93.3, and Visual Memory = 102.8.

Patients with left hemisphere damage were screened for language disorders. To be included in the study, a patient had to score 85 or higher (norm = 100) on the Western Aphasia Battery (Kertesz, 1982). Although this criterion excluded patients with moderate-to-severe aphasia, 2 (J. D. and A. L.) of the 4 patients with left hemisphere lesions who were included were mildly dysfluent and had some difficulty in word finding. Patients with frontal lobe lesions named fewer items spontaneously on the Boston Naming Test (BNT; Kaplan, Goodglass, & Weintraub, 1983) than did control individuals, t(15) = 3.86, p < .005 (all t tests were two-tailed). Average scores (out of 60) were 48.8 correctly named pictures for patients with left hemisphere lesions and 51.5 correct for patients with right hemisphere lesions.

On tests sensitive to frontal lobe damage, patients were relatively impaired relative to control individuals. Patients produced fewer words overall than control individuals on the Letter Verbal Fluency test (Benton & Hamsher, 1978), t(15) = 3.41, p < .01. Patients also were impaired relative to control individuals on the Digit Span subtest of the WAIS-R, t(15) = 2.33, p < .04. On the Wisconsin Card Sorting Test (WCST; Heaton, 1981), patients with frontal lobe lesions achieved marginally fewer categories, t(15) = 1.82, p = .09, and had a marginally greater percentage of perseverative errors, t(15) = 1.79, p = .09.

Control Group A

Eleven healthy volunteers (7 men and 4 women) participated as the primary control group. These individuals were recruited at a Veterans Affairs outpatient clinic. Control individuals were matched to patients with frontal lobe lesions with respect to age (55–75; M = 64.1 years) and education (M = 14.4 years). Nonetheless, control individuals performed significantly better than patients with frontal lobe lesions on two subsets of the WAIS-R that are generally considered to be good measures of premorbid intellectual ability: the Information subtest, t(15) = 2.35, p < .05, and the Vocabulary subtest, t(15) = 2.97, p < .01. Rather than indicating impaired intellectual function in these patients, the Information and Vocabulary subtests may have been sensitive to deficits in verbal expression evidenced by the patients on the BNT and FAS Verbal Fluency test. This hypothesis was supported by significant correlations between performance on the BNT and Vocabulary subtest in both patients (r = .91, p < .02) and control individuals (r = .72, p < .02). Performance on the BNT also was significantly correlated with performance on the Information subtest when participant groups were combined for analysis (r = .65, p < .005). Performance on the Verbal Fluency test was not significantly correlated with either WAIS-R subtest in either volunteer group (p > .05).

Control Group B (Incidental Tasks Only)

An additional 22 volunteers (14 men and 8 women; age range: 56–75) were recruited from the Toronto community to serve as a second control group. These participants received only incidental learning tasks in an effort to eliminate the possibility of carryover effects from earlier intentional testing experience. They were matched to the primary control group (Control Group A) with regard to age, education, and performance on psychometric tests (p > .1; see Table 1). Comparisons between patients and Control Group B on these measures demonstrated the same patterns as observed with Control Group A, except for the percentage of perseverative errors on the WCST. When compared with Control Group B, the patients exhibited a significantly higher percentage of perseverative errors, t(26) = 2.65, p < .02.

Materials

The stimuli consisted of 200 common, concrete nouns taken from the Battig and Montague (1969), K. P. Hunt and Hodge (1971), and Shapiro and Palermo (1970) category norms. From this word pool, eight different lists of 20 words were created. Because of word selection constraints, items for the intentional learning tasks were taken from Battig and Montague, and items for the incidental learning tasks were taken from both the Hunt and Hodge and Shapiro and Palermo norms. Related lists were composed of five items from each of four different semantic categories. Unrelated lists were composed of a single item from each of 20 semantic categories that differed from each other and from those used in the related lists. Sample lists from each condition are shown in the Appendix. Although different lists were used in each condition, every effort was made to match all lists with regard to mean category production frequency (Battig & Montague, 1969) and mean word frequency (Kucera & Francis,
Figure 1. Computerized lesions of patients with frontal lobe damage reconstructed from computed tomography scans and magnetic resonance images. The numbered lines on the lateral view indicate the corresponding axial cuts from the most inferior cut (1) to the most superior cut (7). For the averaged reconstruction (bottom), all lesions have been reflected to the left hemisphere to illustrate the area of greatest overlap.
An additional 40 words were reserved as distractors for the item recognition tests. For each list, distractors were chosen from the same categories as targets and were selected to match targets on mean category production frequency and mean word frequency (p > .1).

For each condition, 11 different list orders for the related and unrelated lists were created. The same list orders were administered to the patients and the control groups. Although the overall organization of categorized items was unblocked, there were three instances in the list on which two items from the same category were presented sequentially (e.g., lake, mountain). None of these three groupings occurred in immediate succession to each other or within the first or last four positions in the list. This method of list construction was based on results from an unpublished pilot study with young participants indicating that list structure influenced the type of errors participants made on order reconstruction of a multiple category list. In this pilot study, participants made significantly more "clustering" errors in order reconstruction (i.e., remembering two items from the same category as sequential that were not presented sequentially in the list) when the list was structured in the manner described earlier than when items from the same category were never presented in sequential positions.

**Design and Procedure**

Patients and Control Group A received the tests in the following order: (a) intentional temporal order memory, (b) incidental temporal order memory, (c) intentional item memory, and (d) incidental item memory, with at least 1 month elapsing between each test. For a given test, participants were tested on a related and unrelated list with at least 2 weeks separating testing of each list. Testing order of related and unrelated lists was counterbalanced such that half of the individuals in each group received the related list first and half received the unrelated list first.

Because of possible contamination of incidental learning by previous exposure to a similar intentional task, I tested an additional control group on the incidental tasks alone (Control Group B). Participants in this group received either incidental temporal order or item memory tasks. Both related and unrelated lists were tested in a single session in a counterbalanced order. To reduce possible carryover effects and interference from the first incidental task to the second, I separated testing of the two incidental learning experiments with a set of tasks that included neuropsychological tests (e.g., WAIS-R subtests, Verbal Fluency...
test, WCST) and an additional cognitive estimation task. This cognitive estimation task was identical to that used in the second incidental learning task, except that participants were not subsequently tested. Therefore, participants would be less likely to expect a subsequent test when the second incidental task was administered later in the session. Nonetheless, the possibility of carryover effects from one incidental task to the next was evaluated statistically in all groups.

**Intentional Learning**

During the study phase, participants viewed stimuli printed in 24-point Palatino letters on 4 × 7 in. (10.16 × 17.78 cm) index cards at a rate of 6 s per word. Participants were fully informed about the nature of the memory task. For the temporal order test, participants were asked to try to remember the order of presentation of the items so that they could reconstruct this order at testing from a randomly ordered array of the same items. For the item memory test, participants were asked to try to remember the items for a later recall and recognition test. Participants were tested after a 1-min interval filled with conversation.

**Temporal order reconstruction test.** The studied words were displayed individually in a random array on 4 × 7 in. (10.16 × 17.78 cm) index cards attached to a 3 × 5 ft (0.91 × 1.52 m) board in a 4 × 5 matrix. Participants were asked to reconstruct the presentation sequence from memory by removing the cards from the board and stacking them in hand such that the item they remembered as presented first was on the top of the stack and the item they remembered as presented last was on the bottom of the stack. Participants sorted the cards until they were satisfied with their reconstructed order.

**Item recall and recognition tests.** Participants were asked to report as many of the items from the list as they could recall without regard to order. When participants reported that they could not recall any additional items and a minimum of 3 min had passed, they were given a recognition test for the items. In the recognition test, items were presented individually on index cards. Targets were randomly interspersed with an equal number of distractors. Participants were asked to try each word aloud and said “old” if they remembered seeing the word on the list and “new” if they did not.

**Incidental Learning**

The format of the incidental learning tasks was basically identical to the intentional learning tasks in terms of presentation duration, study–test delay, and test parameters. However, the following additional measures were incorporated to reduce carryover effects from intentional to incidental learning and from one incidental learning task to the next. First, items in the incidental learning condition were presented on a Macintosh SE-30 computer rather than on index cards. Second, across testing sessions, the incidental tasks were interspersed with a variety of other unrelated tasks. Finally, the two different word lists (related and unrelated) were counterbalanced with two different semantic orienting tasks (pleasantness and size judgments).

**Order and type of orienting task was counterbalanced across lists and participants.** The size judgment task required participants to decide whether an item was larger or smaller than an average human (order test) or shoebox (item test). This variation in comparison object across the two size judgment tasks was necessary to obtain different sets of study items for the order and item memory tests. The pleasantness judgment orienting task required participants to decide whether an item was relatively pleasant or unpleasant. This orienting task was identical in both item and order tests.

For both orienting tasks, participants were instructed to image the referent of the word and think about the pleasantness or size of the referent while the word was on the computer screen. Each word was followed by a question mark that served as response signal to press a button on a response box. Participants were asked to make their responses as quickly and accurately as possible. As soon as participants made their response, the next word appeared on the computer screen. This procedure was done to equate encoding time across the incidental and intentional learning tasks.

Although previous studies have shown that patients with frontal lobe lesions are impaired on cognitive estimation tasks that require them to generate a specific numerical estimate (Shallice & Evans, 1978; Smith & Milner, 1984), recent studies have failed to replicate these findings using large groups of patients with anterior lesions (Taylor & O’Carroll, 1995). Nonetheless, to reduce demands on strategic retrieval and evaluation (i.e., metamemory) processes in the current research, I asked participants only to make a simple two-choice decision (e.g., larger or smaller). McAndrews and Milner (1991) demonstrated normal size discrimination in patients with frontal lobe lesions when tested with a similar two-choice task.

Patients with frontal lobe lesions did not make any errors on this simplified size judgment task. One control group member, however, made errors on 25% of the items, was continually distressed by her errors, and talked during much of the task. She was dropped from further analysis for failure to perform the task like the other participants. Her elimination did not affect comparisons of patient and control group performance on the neuropsychological tests described earlier.

**Temporal order reconstruction test.** The procedure for order reconstruction was identical to that used in the intentional learning condition.

**Item recall and recognition tests.** The procedure for item free recall was identical to that used in the intentional learning condition. For the item recognition test, individual targets and distractors were presented randomly on the computer screen. Participants responded by pressing a button on the response box (left button = old, right button = new).

**Debriefing.** At the conclusion of the incidental learning tasks, participants were asked whether they had expected a memory test, tried to study the words in any way during the judgment task, or both. After the temporal order test, no one reported actively memorizing the words during the encoding task. At the conclusion of the item memory tests, however, 1 patient, 3 participants in Control Group A, and 1 participant in Control Group B reported that they had anticipated a memory test during presentation of one or both lists. To reduce the possibility of contamination from intentional learning, I excluded these participants from all analyses involving incidental item memory.

**Data Analysis**

**Overall Performance**

Overall memory for temporal order was measured by two methods: (a) the Pearson’s product–moment correlation between participants’ remembered order and actual list order (1.0 = perfect order, 0.0 = random organization) and (b) the sum of the absolute value of the difference between each item’s remembered position and its actual position (i.e., deviation). Overall item memory was measured as the percentage correct in item free recall (number of items recalled out of 20) and the percentage of hits (correct
responses) minus false alarms (calling a new item old) in item recognition.

Serial Organization

In order reconstruction, serial organization was calculated as the number of pairs of items that were presented in sequential positions at study and were reconstructed sequentially, in their correct order, at test (minimum = 0, maximum = 19; Kihlstrom & Wilson, 1984). This measure was not corrected for number of items retrieved because all items were provided to participants at testing. Serial organization in free recall were calculated similarly, but without regard to the order of items within the pairs and taking into account chance levels given the total number of items recalled (maximum = 17.1). This measure was derived from Sternberg and Tulving’s (1977) measurement of subjective organization by Gershberg and Shimamura (1995).

Semantic Organization

Semantic clustering in order memory was measured as the number of instances in which two items from the same category were ordered in sequential positions at test, without regard to the exact order of presentation (i.e., category clusters). This score was not adjusted for number of items retrieved because all items were provided to participants at test. The total number of category clusters was divided further into instances of correct clustering, in which participants correctly reconstructed two category members in sequential order that were sequentially presented at study (e.g., mountain, lake [maximum = 3]; see the Appendix) and clustering errors, in which participants incorrectly reconstructed two category members in sequential order that were not presented sequentially at study (e.g., canyon, valley; see the Appendix). Although it is unusual to apply this measure to temporal order, it is relevant to the hypotheses of this research. Specifically, if semantic interitem associations interfere with serial associations, participants may make a high number of clustering errors in order reconstruction of the related list (i.e., sequentially ordering items from the same category at testing that were not presented in succession at study). In item free recall, semantic organization was measured using the adjusted ratio of clustering (ARC) method developed by Roenker, Thompson, and Brown (1971). The ARC measure defines semantic organization as the extent to which items from the same category are grouped together at recall while taking into account the total number of items recalled and chance clustering levels (maximum = 1.0).

Results

Temporal Order Memory

Intentional Learning

Table 2 shows order reconstruction performance for the patients and the control groups, as measured by the correlation between the remembered and actual order. One control participant was excluded from the analysis of this experiment for performing more than 3 SDs below the mean for the control group on order reconstruction of the related list. Exclusion of this outlier did not affect overall differences between patients and control individuals on the standardized tests described earlier.

Patients were disproportionately impaired on order reconstruction of the semantically related list. When temporal order performance was measured by correlation, a 2 (group) X 2 (list) mixed-design analysis of variance (ANOVA) demonstrated a significant overall effect of group, F(1, 14) = 4.88, MSE = 0.18, p < .05, list, F(1, 14) = 4.44, MSE = 0.06, p = .05, and a significant interaction between interitem semantic relatedness and participant group, F(1, 14) = 5.11, MSE = 0.07, p < .05. Investigation of this interaction revealed that patients were impaired relative to control participants on the related list, t(14) = 2.74, p < .02, but that they performed comparably to control participants on the unrelated list, t(14) = 0.82, p = .42. The identical pattern of results were obtained using the deviation measure.

Control participants appeared to rely heavily on serial organization to reconstruct the order of both related and unrelated lists. As shown in Table 3, control participants exhibited a greater number of serial associations in order reconstruction than did the patients. This observation was confirmed by a 2 (group) X 2 (list) ANOVA demonstrating a

### Table 2

<table>
<thead>
<tr>
<th>Patient</th>
<th>Lesion</th>
<th>Intentional learning</th>
<th>Incidental learning</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Related list</td>
<td>Unrelated list</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Correlations</td>
<td></td>
</tr>
<tr>
<td>O.A.</td>
<td>Left</td>
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<td>.708</td>
</tr>
<tr>
<td>J.D.</td>
<td>Left</td>
<td>.445</td>
<td>.704</td>
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<tr>
<td>A.L.</td>
<td>Left</td>
<td>.877</td>
<td>.798</td>
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<tr>
<td>R.M.</td>
<td>Left</td>
<td>.495</td>
<td>.639</td>
</tr>
<tr>
<td>E.B.</td>
<td>Right</td>
<td>.209</td>
<td>.820</td>
</tr>
<tr>
<td>M.M.</td>
<td>Right</td>
<td>.615</td>
<td>.788</td>
</tr>
</tbody>
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Means (SEs in parentheses):

- Patients: .534 (.089), .741 (.028), .364 (.120), .444 (.068)
- Control Group A: .785 (.047), .800 (.052), .366 (.072), .442 (.092)
- Control Group B: -.003, -.003, .308 (.066), .405 (.098)

Note. Dashes indicate that data were not available or not applicable.
significant effect of group on pairwise serial organization, $F(1, 14) = 8.76, MSE = 19.58, p < .02$. There was no main effect of list, $F(1, 14) = 0.35, MSE = 4.36, p = .56$, or Group × List interaction, $F(1, 14) = 0.21, MSE = 4.36, p = .65$. In addition, for control participants, serial organization and overall order performance were strongly correlated regardless of list type (related list, $r = .71, p < .02$; unrelated list, $r = .80, p < .006$). The relationship between serial organization and overall order performance was weaker in patients (related list, $r = .65, p = .16$; unrelated list, $r = .58, p = .23$) than control individuals.

These findings suggest that the patients relied less on the use of a serial organizational strategy to reconstruct the order of the unrelated list than did the control groups. Instead, the patients may have based their order reconstruction on knowledge of the general position of items (i.e., beginning, middle, end). To assess position knowledge directly, I conducted a post hoc analysis of serial position in order memory. An estimate of serial position performance was obtained by dividing the 20 list positions into five equal sections of four positions each (i.e., first set of four positions, second set of four positions, etc.) and summing the deviations over each of the four items in each of these five sections. A 2 (group) × 5 (position) post hoc analysis confirmed that the patients performed comparably to the control groups on all serial positions in the unrelated list, $F(1, 14) = 1.66, MSE = 111.44, p = .22$. There was a significant effect of serial position, $F(1, 14) = 2.77, MSE = 31.0, p < .04$, due to a primacy effect in both groups ($p < .05$). Serial position did not interact with group, $F(4, 56) = 1.78, MSE = 31.0, p = .15$.

The patients may have been disproportionately impaired on order reconstruction of the serially organized list because of heightened sensitivity to interference from semantic interitem associations. This conclusion was supported by the pattern of semantic clustering that the patients demonstrated in order reconstruction of this list. As illustrated in the left side of Figure 2, although the patients and control participants demonstrated an equal amount of total clustering, $F(1, 14) = 0.24, MSE = 0.72, p = .63$, there was a significant Subject Group × Clustering Type interaction, $F(1, 14) = 12.65, MSE = 1.25, p < .004$. Specifically, the patients achieved fewer correct clusterings, $t(14) = 3.12, p < .008$, and made more clustering errors, $t(14) = 2.70, p < .02$, than did control individuals.

### Incidental Learning

Analysis of temporal order reconstruction as a function of orienting task and testing order did not reveal any significant findings ($p > .1$); I therefore collapsed the data over these variables. In particular, there was no indication that participants performed better on the second incidental learning task, regardless of whether the second task was given in the same (Control Group B) or a separate (patients and Control Group A) session. Thus, it appears that the structure of the test session was successful in eliminating carryover effects from one incidental task to the next.

Under incidental learning conditions, memory for temporal order in the patients did not differ from either control group (see Table 2). A 3 (group) × 2 (list) ANOVA using correlation scores showed no effect of group, $F(2, 24) = 0.23, MSE = 0.06, p = .80$, or list, $F(2, 24) = 1.32, MSE = 0.08, p = .26$, and no interaction between list and group, $F(2, 24) = 0.09, MSE = 0.08, p = .99$. The same pattern of effects was found when deviation scores were analyzed.

Although caution must be observed in interpreting a null effect with a small sample size, numerous points suggest that group differences were not obscured by low experimental power. First, the overall performance of the patients (using correlation scores) was essentially identical to that of the control groups (patients = .40, Control Group A = .40, Control Group B = .36), and the performance of all groups was above chance, in which chance is equal to a random correlation; patients, $t(5) = 6.00, p < .002$; Control Group A, $t(9) = 7.38, p < .001$; Control Group B, $t(10) = 6.26, p < .001$. Second, performance was replicated across both control populations. Finally, performance variability was homogeneous across both control and list ($F_{max} = 1.82$), and average variance under incidental learning conditions did not greatly differ from the variance under intentional learning conditions (the average variances for intentional and incidental learning were .05 and .09, respectively).

Organization in order reconstruction also was similar in the patients and control groups under incidental learning conditions (see Table 3). A 3 (group) × 2 (list) ANOVA revealed that the patients produced a significantly greater number of serial associations than either control group, $F(2, 24) = 3.55, MSE = 1.94, p < .05$. There was no effect of list, $F(2, 24) = 2.02, MSE = 1.55, p = .16$, or interaction between list and group, $F(2, 24) = 0.05, MSE = 1.55, p = .

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### Table 3

**Mean Serial Organization in Memory for Temporal Order**

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<th></th>
<th>Intentional learning</th>
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<tr>
<td></td>
<td>Related list</td>
<td>Unrelated list</td>
</tr>
<tr>
<td><strong>Group</strong></td>
<td>$M$</td>
<td>$SE$</td>
</tr>
<tr>
<td>Patients</td>
<td>2.67</td>
<td>0.49</td>
</tr>
<tr>
<td>Control Group A</td>
<td>7.10</td>
<td>1.07</td>
</tr>
<tr>
<td>Control Group B</td>
<td>0.91</td>
<td>0.29</td>
</tr>
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</table>

**Note.** Dashes indicate that data were not applicable.
Low correlations between overall order performance and serial organization in all groups (range = -0.32 to 0.52), however, indicated that neither the patients nor control participants used serial associations to reconstruct the order of the list. Low levels of serial organization may have resulted partly from the encoding tasks themselves. Both size and pleasantness judgments may have emphasized item-specific processing, as opposed to relational, associative processing (e.g., Einstein & Hunt, 1980; R. R. Hunt & Einstein, 1981). Thus, patients may have performed normally on this task because demands on relational processing at encoding were minimized.

Patients and control participants produced identical patterns of semantic clustering under incidental learning conditions, $F(2, 24) = 0.80, \text{MSE} = 3.18, p = 0.46$. As illustrated in the right side of Figure 2, all groups made many clustering errors and demonstrated little knowledge of correct semantic organization. There was no interaction between group and cluster type, $F(2, 24) = 0.84, \text{MSE} = 2.40, p = 0.45$.

To assess the effects of intention to learn on memory for temporal order, I compared order reconstruction performance of patients and Control Group A under incidental and intentional learning conditions. A post hoc three-variable ANOVA, with two experiments, two groups, and two lists, demonstrated that order reconstruction performance was significantly lower in both groups under incidental learning conditions, compared with intentional learning conditions, $F(1, 13) = 53.9, \text{MSE} = 0.03, p < .001$. However, a marginally significant interaction between group and experiment, $F(1, 13) = 4.09, \text{MSE} = 0.03, p < .07$, suggested that the performance of the control groups was reduced to a greater extent than that of the patients.

Post hoc comparisons of serial and semantic organization across learning conditions demonstrated this interaction more convincingly. For serial organization, a 2 (experiment) X 2 (group) X 2 (list) ANOVA revealed a significant main effect of encoding instruction, $F(1, 13) = 20.23, \text{MSE} = 9.14, p < .001$, and interaction between subject group and instruction, $F(1, 13) = 16.64, \text{MSE} = 9.14, p < .002$. Specifically, when collapsed over list, control participants exhibited significantly less serial organization under incidental learning conditions, $F(1, 17) = 58.40, \text{MSE} = 7.19, p < .001$, but the patients demonstrated equal serial organization regardless of intention to learn, $F(1, 11) = 0.18, \text{MSE} = 3.67, p = .68$.

When clustering in the related list was examined in a similar analysis, a significant three-way interaction among experiment, subject group, and list emerged, $F(1, 13) = 19.59, \text{MSE} = 1.65, p < .001$. Under incidental learning instructions, control individuals produced a significantly lower number of correct clusters, $F(1, 8) = 28.00, \text{MSE} = 0.39, p < .001$, and significantly greater number of clustering errors, $F(1, 8) = 11.88, \text{MSE} = 2.26, p < .009$, than under intentional learning instructions. By contrast, the clustering performance of the patients did not differ as a
Table 4
Individual Performance and Group Means on Item Free Recall and Recognition Following Intentional and Incidental Learning

<table>
<thead>
<tr>
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<tr>
<td></td>
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<td>% Recognition</td>
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<td>Unrelated list</td>
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</tr>
<tr>
<td>J.D.</td>
<td>Left</td>
<td>20 20 60 100</td>
</tr>
<tr>
<td>A.L.</td>
<td>Left</td>
<td>60 40 95 100</td>
</tr>
<tr>
<td>R.M.</td>
<td>Left</td>
<td>35 30 60 70</td>
</tr>
<tr>
<td>E.B.</td>
<td>Right</td>
<td>65 15 65 50</td>
</tr>
<tr>
<td>M.M.</td>
<td>Right</td>
<td>25 20 70 70</td>
</tr>
<tr>
<td>Patients</td>
<td>--</td>
<td>44.2 (8.1) 22.5 (4.4)</td>
</tr>
<tr>
<td>Control Group A</td>
<td>--</td>
<td>79.5 (2.9) 55.0 (6.1)</td>
</tr>
<tr>
<td>Control Group B</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Note. Dashes indicate that data were not available or not applicable.

Item Memory

Intentional Learning

Item free-recall and recognition performance are shown in Table 4. A 2 (group) × 2 (list) ANOVA revealed that the patients were impaired relative to control participants on item free recall under intentional learning, F(1, 15) = 40.01, MSE = 8.94, p < .001. The rate of intrusions in free recall also was greater in patients than control individuals, F(1, 15) = 5.05, MSE = 0.02, p < .05. These findings are consistent with the free-recall deficits observed in patients with frontal lobe lesions from previous studies (e.g., Gershberg & Shimamura, 1995; Incisa della Rocchetta & Milner, 1993; Jetter, Poser, Freeman, & Markowitsch, 1986; Stuss, Alexander, et al., 1994).

As expected, free-recall performance was higher on the related list than the unrelated list, F(1, 15) = 16.90, MSE = 11.14, p < .001, and there was no interaction between group and list, F(1, 15) = 0.06, MSE = 11.14, p = .81. In addition, semantic relatedness did not result in a greater number of intrusions, F(1, 15) = 1.13, MSE = 0.02, p = .30. Both groups benefited equally from semantic similarity in the related list.

Despite impaired item free recall in the patients, a 2 (group) × 2 (list) ANOVA revealed that the patients and control participants demonstrated comparable levels of serial organization in the free-recall protocol, F(1, 15) = 1.11, MSE = 8.60, p = .30 (see Table 5). However, serial organization in free recall was relatively low in both groups, suggesting that this type of organization was less critical for item free-recall performance than order reconstruction performance. In addition, control participants may have used strategies in the free-recall task that were orthogonal to serial organization. Post hoc analyses indicated that serial organization and category clustering in the related list were correlated negatively in control participants (r = -.91, p < .001), but not in the patients (r = .42, p = .41). In the unrelated list, control participants may have used higher order strategies (e.g., subjective organization) that competed with serial organization but that were not apparent because of the single-trial design.

The patients also demonstrated comparable levels of semantic organization (ARC) in free recall, F(1, 15) = 0.20,
MSE = 0.12, p = .67 (see Table 5). Although previous evidence for category clustering deficits in patients with frontal lobe lesions is mixed (Gershberg & Shimamura, 1995; Jetter et al., 1986; Stuss, Alexander, et al., 1994), it is possible that the use of highly associated category members and the three sequential presentations of category members alerted the patients to the categorized structure of the list.

Finally, previous studies of temporal order in patients with frontal lobe lesions have cited normal performance on item recognition tests as evidence for a selective deficit in order memory (e.g., Kesner et al., 1994; Shimamura et al., 1990). In the current research, however, the patients were impaired on item recognition, F(1, 15) = 5.67, MSE = 250.3, p = .04. In addition, both groups were marginally poorer on recognition of items from the related list, F(1, 15) = 3.88, MSE = 118.52, p = .07. However, there was no interaction between group and list, F(1, 15) = 0.0008, MSE = 118.52, p = .98. It is possible that the marginal recognition deficits observed in this group of patients resulted from the increased difficulty of discrimination caused by the semantic relatedness of the distractors. However, when false alarms were analyzed separately, no group differences emerged, F(1, 15) = 0.65, MSE = 3.7, p = .43. Although both groups made more false alarms in the related list than the unrelated list, F(1, 15) = 12.36, MSE = 3.1, p < .004, there was no interaction between group and list, F(1, 15) = 1.17, MSE = 3.7, p = .30.

Although the patients were impaired on item recognition, it is unlikely that their pattern of order performance can be explained by poor memory for the items themselves. Whereas semantic relatedness disproportionately impaired temporal order reconstruction in the patients, there was no interaction between group and relatedness in item recognition performance.

**Incidental Learning**

Analysis of item free-recall and recognition performance by orienting task did not reveal any significant effects (p > .2); therefore, I collapsed the data over this variable. There were no effects of testing order on item recognition (p > .1). For item free recall, however, a marginally significant interaction emerged between group and testing order, F(1, 18) = 3.41, MSE = 0.01, p = .08. When tested second, item free recall of the unrelated list was significantly poorer in Control Group B, t(9) = 2.70, p < .03, and marginally poorer in the patients, t(3) = 2.72, p = .07, compared with when this list was tested first. By contrast, the free recall of related items did not differ as a function of test order in any group, t(9) = 1.03, p > .33. For Control Group A, there was no effect of test order (p > .8). These findings indicate that participants were not covertly using encoding strategies to facilitate learning of the second list. However, they also suggest that proactive interference differentially impairs item memory for recall of information that places greater demands on strategic retrieval (i.e., the unrelated list). Proactive interference may have been greatest in Control Group B because both lists were tested in a single session.

Given that Control Group B demonstrated differential carryover effects of test order on item free recall, I analyzed the results of this group separately.

Unlike memory for temporal order, incidental learning did not eliminate differences in performance between the patients and Control Group A on item free recall (see Table 4). A 2 (group) × 2 (list) ANOVA demonstrated a significant effect of subject group, F(1, 10) = 11.77, MSE = 5.3, p < .007, and list, F(1, 10) = 23.86, MSE = 1.47, p < .001. There was no interaction between group and list, F(1, 10) = 1.47, MSE = 4.54, p = .25. Intrusions in free recall were low and equivalent across groups, F(1, 10) = 1.59, MSE = 0.0004, p = .24. Comparison of the patients with Control Group B revealed an identical pattern of findings.

Deficits of the patients on overall item free recall did not appear to result from differential use of serial and semantic organizational strategies (see Table 5). When words were encoded incidentally, no group appeared to be able to access serial associations at retrieval. As indicated by a 2 (group) × 2 (list) ANOVA, both the patients and Control Group A demonstrated equally low (below-chance) levels of serial organization, F(1, 10) = 0.16, MSE = 0.58, p = .70. There was no effect of list, F(1, 10) = 0.16, MSE = 0.32, p = .70, or interaction between group and list, F(1, 10) = 2.06, MSE = 0.32, p = .18. Although Control Group B demonstrated above-chance levels of serial organization, their performance was only marginally different from that of the patients, F(1, 13) = 3.39, MSE = 0.54, p < .09. Semantic clustering exhibited by the patients also was equivalent to that of Control Group A, F(1, 11) = 0.02, MSE = 0.14, p = .88, and Control Group B, F(1, 13) = 0.10, MSE = 0.22, p = .76.

There was no overall group difference on item recognition, F(2, 19) = 2.16, MSE = 136.53, p = .14. However, there was a weak trend toward better group performance on the unrelated list, F(1, 19) = 2.83, MSE = 45.10, p = .10, and a significant interaction between group and recognition performance, F(2, 19) = 4.19, MSE = 45.10, p < .04. Investigation of this interaction revealed that the patients were marginally impaired on recognition memory for the related list compared with Control Group B, t(12) = 2.0, p = .07, but not Control Group A, t(10) = 1.5, p = .19. Recognition memory for the unrelated list was similar across all groups (p > .1), although ceiling effects in this condition may have obscured larger differences. There was no difference in the overall false-alarm rate of the patients and control groups, F(2, 19) = 1.35, MSE = 0.72, p = .87, and no interaction between group and list, F(1, 19) = 0.87, MSE = 0.36, p = .44. Both groups made more false alarms in the related list, F(1, 19) = 4.00, MSE = 0.36, p = .06.

To assess the effects of intention to learn on item memory, I compared the performance of the patients and Control Group A in a series of post hoc three-variable ANOVAs, with two groups, two lists, and two encoding conditions. These analyses revealed that incidental learning conditions affected the item free-recall performance of control participants to a greater extent than that of the patients, F(1, 10) = 5.6, MSE = 5.8, p < .04, suggesting that the patients encoded item information nonstrategically regardless of
intention to learn. Nonetheless, although incidental learning conditions reduced item free recall in control participants, it did not bring their performance down to the level of the patients. Again, the superior performance of control participants under incidental and intentional learning did not appear to result from greater strategy use in control participants. Serial organization and semantic clustering were unaffected by intention to learn in either group (p > .4). Finally, item recognition performance was equally unaffected by intention to learn in the three groups, F(1, 10) = 0.39, MSE = 306.3, p = .55. Potential differences in these analyses may have been obscured, however, by ceiling effects in the performance of the control groups under incidental learning.

Discussion

The results of the current research provide an important step toward clarifying the role of the dorsolateral prefrontal cortex in the temporal organization of memory. Although automatic processing of temporal information is intact in patients with dorsolateral prefrontal lesions, strategic organization of this information is impaired. Two aspects of the data—overall order reconstruction and serial organization—support this conclusion. Patients with frontal lobe lesions demonstrated normal memory for temporal order when items were encoded under incidental learning conditions, indicating that they could form basic temporal codes as well as control participants. When items were encoded under intentional learning conditions, however, the control participants exhibited a significant advantage in overall order reconstruction that appeared to result from their effective use of serial associative strategies. Serial organization was not apparent in the temporal order reconstruction performance of the patients regardless of intention to learn. Thus, unlike the control participants, the patients did not appear to augment automatically formed temporal codes with appropriate strategic processing when they were informed of an upcoming temporal order test.

Impaired memory for temporal order in the current group of patients with frontal lobe lesions primarily was due to strategic deficits at encoding rather than at retrieval. Deficits of these patients on both overall temporal order reconstruction and serial organization were eliminated by manipulation of encoding instruction alone (i.e., under incidental learning conditions; also see Butters et al., 1994; McAndrews & Milner, 1991). Nonetheless, numerous researchers have associated the prefrontal cortex with the ability to retrieve information in its correct temporal context (Moscovitch, 1989; Partiot, Grafman, Sadato, Flitman, & Wild, 1996; Shimamura et al., 1990; Sirigu et al., 1995). In the current test of temporal order memory, demands on strategic organization at retrieval may have been reduced because all items were provided at test. Demands at retrieval are greater when items must be generated from memory, as in tests of item free recall (e.g., Gershberg & Shimamura, 1995; Mangels, Gershberg, Shimamura, & Knight, 1996). Indeed, the patients in the current study demonstrated impaired item free recall regardless of encoding instruction.

The patients demonstrated impaired strategic organization, however, only in memory for temporal order. Levels of serial organization in item free recall, although low, were comparable in the three groups across both encoding conditions. Gershberg & Shimamura (1995) also found that patients with frontal lobe lesions demonstrated normal levels of serial organization in item free recall. Unlike serial organization in temporal order, serial organization in free recall does not take into account the precise order in which items were recalled (i.e., both AB and BA receive credit as a serial association). Thus, the organizational deficits of the patients in the current research appeared to be selective to strategies that encoded the specific order of information.

Strategic processing appears to be particularly important for encoding the temporal order of items in a semantically related list. Under intentional learning conditions, temporal order reconstruction of the semantically related list was disproportionately impaired, relative to the unrelated list, in the patients with frontal lobe lesions. The poor performance of the patients on the semantically related list was associated with a high incidence of clustering errors (i.e., sequentially ordering items from the same category at test that were not presented in succession at study), suggesting that the patients based their order reconstruction on semantic activation rather than temporal information. Automatic activation of related items within a preexisting semantic network provides little contextual information about the learning episode, yet it may be strong enough to interfere with automatically formed temporal codes. All three groups demonstrated this pattern of clustering under incidental learning conditions, indicating that semantic interference in order memory was associated with nonstrategic encoding and did not simply result from a particular strategy used by the patients in the intentional learning condition.

Order memory for semantically unrelated information appeared to be less sensitive to strategy use. Frontal patients and Control Group A performed comparably on order reconstruction of the unrelated list regardless of encoding instruction. Furthermore, under intentional learning conditions, the patients exhibited normal order reconstruction of the unrelated list despite impaired levels of strategic organization. This dissociation between overall performance and strategic organization suggests that unrelated items may be sufficiently segmented with regard to list position such that organizational strategies are less necessary to encode temporal order.

These findings implicate item distinctiveness as a critical variable in determining the performance of patients with frontal lobe lesions on tests of temporal order. Unrelated items can be viewed as being relatively distinctive because they share little semantic information (cf. Schmidt, 1991). Distinctive information encourages item-specific processing (Einstein & Hunt, 1980; R. R. Hunt & Einstein, 1981). This type of processing may automatically create temporally distinct representations in memory. By contrast, the semantic overlap between related items may reduce temporal distinctiveness and render automatically formed temporal codes less reliable. Inherent distinctiveness has been proposed as one explanation for the beneficial effects of SPT items on recency discrimination in patients with frontal lobe
damage (Butters et al., 1994; McAndrews & Milner, 1991). The present findings strengthen this interpretation and demonstrate that the positive effects of distinctiveness on memory for temporal order can extend to nonmanipulated items.

In summary, memory for temporal order in patients with frontal lobe lesions was sensitive to semantic relatedness, but not to intention to learn. Thus, deficits in memory for temporal order in patients with frontal lobe lesions appear to result from impaired strategic organization at encoding and are exacerbated by deficits in inhibitory control. Encoding serial relationships among multiple items (i.e., linking items in a storylike fashion) requires that earlier list items be retrieved and held in working memory while associations with the current item are rehearsed. Focusing attention on these episodic relationships may serve to inhibit interference from automatically activated semantic associations.

Deficits in strategic processing and inhibitory control repeatedly have been shown to influence performance on test of item free recall in patients with frontal lobe lesions (Eslinger & Grattan, 1994; Gershberg & Shimamura, 1995; Shimamura et al., 1995; Stuss, Alexander, et al., 1994). My research extends the influence of these deficits to tests of temporal order as well. Indeed, it may be possible to interpret previous findings of impaired memory for temporal order in terms of deficits in strategic processing (Kesner et al., 1994; Milner et al., 1991). Interitem relatedness in previous studies has not been controlled (Milner et al., 1991; Shimamura et al., 1990). For example, in one study, the same items were repeated across multiple study-test trials (Kesner et al., 1994), a procedure that may have led to increased proactive interference in patients with frontal lobe lesions. In addition, recency discrimination tasks that use a continuous presentation place high demands on strategic, relational processing because they require participants to keep track of relationships between a long list of items and constantly update these associations as new items are presented (Milner et al., 1991).

The relationship between frontal lobe function and strategic processing has been developed in a variety of theories about the frontal lobes (see Baddeley, 1986; Moscovitch, 1994; Norman & Shallice, 1986; Shallice & Burgess, 1991; Shimamura, 1994). To my knowledge, my results are the first empirical evidence to indicate that impaired strategic organization at encoding strongly contributes to, and may even account for, deficits in temporal order memory observed in patients with dorsolateral prefrontal lesions. Automatic temporal processing was spared in these patients and may rely on other brain structures. Thus, the dorsolateral prefrontal cortex does not appear to be the sole locus of temporal information processing. Rather, it appears to monitor and organize temporal information in the same way it influences other aspects of information processing.

References


Appendix

Related and Unrelated Items in Sample List Orders

### Table A1
**Temporal Order Memory**

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<thead>
<tr>
<th>Intentional learning</th>
<th>Incidental learning</th>
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</thead>
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<td>Related list</td>
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### Table A2
**Item Memory**

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