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Representation of Linguistic Rules in the Brain: Evidence from Training an Aphasic Patient to Produce Past Tense Verb Morphology

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We trained a patient with expressive aphasia and a deficit in phoneme-to-grapheme conversion to produce spoken English verbs with correct tense morphology. After training, he showed evidence of generalization to production of written regular, but not irregular, verbs in a sentence completion task. These data support dual-route, rule-based models within the brain for morphosyntactic operations. © 1999 Academic Press

INTRODUCTION

Recovery from severe aphasia remains a difficult and unpredictable travail for patients. Current techniques in speech therapy are least successful with the most severely aphasic patients (Basso, Capitani, & Vignolo, 1979). Despite decades of research into the linguistic mechanisms of aphasia, few new therapeutic modalities are available, especially for the most severely afflicted patients. Augmentative language systems, while effective for patients with motor or speech disorders, have generally not been successful with severely aphasic patients (Weinrich, 1997).

Our group developed C-VIC (computerized visual communication) in an attempt to surmount the difficulties faced by conventional communication systems for aphasic patients (see Fig. 1 for an explanation of this system) (Steele, Weinrich, Wertz, Kleczewska, & Carlson, 1989; Weinrich, McCall, Weber, Thomas, & Thornburg, 1995). Using C-VIC, it has been possible to investigate the language capabilities even of globally aphasic patients and to demonstrate that some of them are capable of language-like operations

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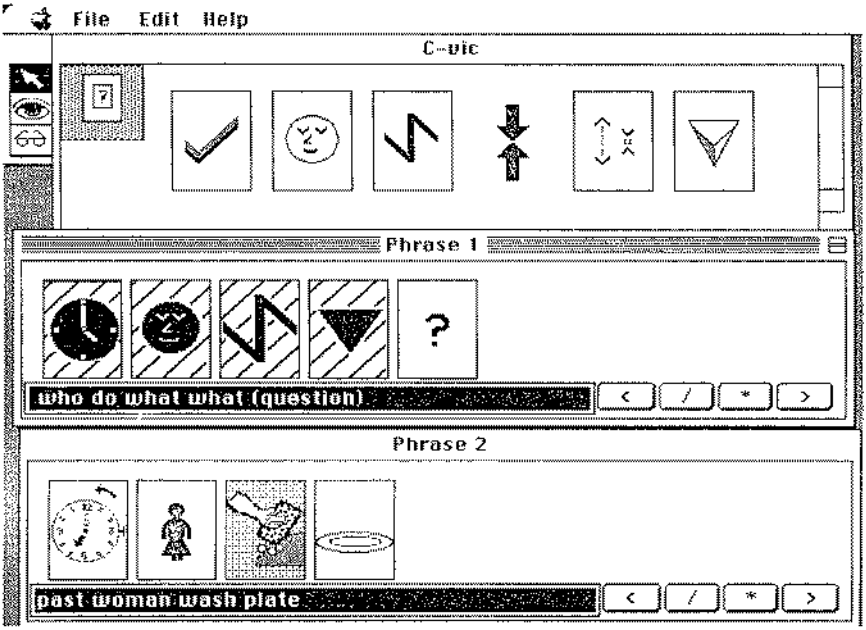

FIG. 1. The C-VIC computer screen as seen by the patient. The top row of symbols indicates categories of icons that can be opened for retrieval by clicking the mouse button. Communications can be formed by dragging icons into the communication spaces below to create strings of icons in serial order. In this example, the therapist has created a template question, ''(When) (who) (did what) (to what)?'' The patient responds in the space below, ''(Past) (woman) (wash) (plate).''

on symbolic systems (Shelton, Weinrich, McCall, & Cox, 1996). Quite unexpectedly, we found that training with C-VIC improves the verbal production of some patients with severe expressive aphasias (Weinrich, Shelton, Cox, & McCall, 1997). However, it has been difficult to demonstrate that this improvement, so readily demonstrable in the laboratory, translates into real functional improvement in patients' language.

To understand the mechanism and limits of improvement in language production with C-VIC training, it is first necessary to place this training in the context of a theory of language production and aphasic deficits. Contemporary neuropsychological theories of language, based heavily upon analyses of speech errors in normal speakers (Fromkin, 1973; Garett, 1975) and priming studies (Levelt, 1989; Jescheniak & Levelt, 1994) of normal individuals, have specified in considerable detail the processes subserving production of words in sentences (Bock 1982; Bock & Levelt, 1994). Figure 2 illustrates the outline of the currently dominant model. In this model, a nonlinguistic message is first conceived. A *functional* representation is then constructed. This representation does not contain actual word forms, but rather the *lem-*

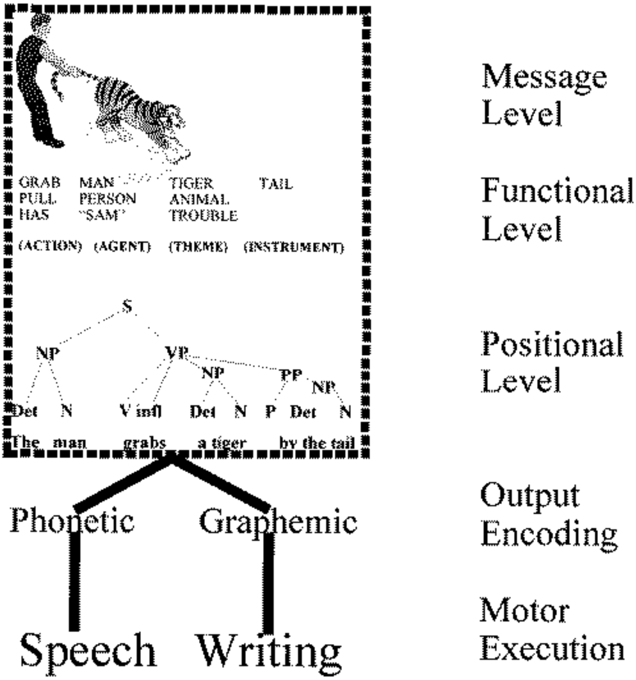

FIG. 2. Production of a sentence according to the dominant contemporary model. A nonlinguistic message is first formulated into a functional level representation. To assemble this representation, lemmas of words are retrieved from the lexicon. Each group of vertically arranged elements demonstrates some of the information (semantic, grammatical class, gender, etc.) contained in the lemma representation. Only at the positional level is a syntactic frame assembled and word forms retrieved from the lexicon and inserted into it. After a complete positional representation is constructed it can be encoded for motor output in speech or writing.

mas of words, i.e., information about the words' meanings, grammatical classes, argument structures, genders, cases, etc. After the functional representation is complete, it is mapped onto an entirely separate representation containing word forms (lexemes). It is this second, *positional* representation in which the grammatical encoding takes place, including ordering words and encoding morphological indicators of syntactic/semantic relations such as inflection.

Representations at either the functional or the positional levels of aphasic patients may have abnormally fast decay rates leading to failures of language production (Martin, Dell, Saffran, & Schwartz, 1994). Since construction of correct C-VIC communications indicates that patients can form intact messages, and there is no explicit training in our protocols of English rules for syntax, we have argued that the improvements in English production demonstrable after C-VIC training indicate that C-VIC training must serve to stabilize functional representations or to somehow strengthen the connections between functional and positional representations. Examination of aphasic patients' abilities to generalize English rules for morphosyntax to untrained items and across different modalities can allow us to more precisely define the level at which C-VIC training improves language function.

Verb tense morphology provides a particularly interesting opportunity to study the effects of C-VIC training, because the formation of verb tense morphology, especially past tense, has been a lively skirmish ground between proponents of dual-route linguistic theories, who suggest that regular verbs are formed by the action of abstract linguistic rules operating in the brain (Pinker & Prince, 1988), and proponents of distributed processing models, who replace abstract rules with patterns learned by neural networks after repeated exposures to words (Rumelhart & McClelland, 1986). Thus, in the dual-route models, words composed of stems and affixes, such as *poured* are stored as a stem, *pour* together with a rule (regular verb, singular past tense, add *ed*), while the opposing models would have all forms of *pour* stored separately in the lexicon. Proponents of the rule-based, linguistic models have pointed to the peculiar pattern in which children learn irregular verbs and later incorrectly regularize them as they learn the rules for regular verbs (Pinker & Prince, 1988), thus suggesting a *dual-mechanism* that uses a rule for regular verbs and stores the past forms for irregular verbs in the lexicon. This claim has been directly challenged by neural network models, without explicit rules, that have attempted to simulate these patterns of past tense learning (Rumelhart & McClelland, 1986; MacWhinney & Leinbach, 1991). In this context, the language production of aphasic patients may provide another set of data against which these theories may be tested.

We have been studying a patient with expressive aphasia who also has a profound deficit in transferring information between spoken and written modalities (Shelton & Weinrich, 1997). This additional deficit has allowed us to train his verbal production in relative isolation from his writing. After training him with C-VIC to produce verbal English tense-marked sentences, we tested his production of spoken and written English sentences using trained and untrained verbs. To examine the maximum extent to which he could generalize production of verb tense, we then tested his production of verb tense in a sentence completion task, in which other sentence production demands were minimized.

METHODS

Subject

EA is a 65-year-old man who suffered a stroke in 1983. CT scans demonstrate infarction in the posterior left frontal lobe extending into the left anterior temporal lobe and ventral aspect of the basal ganglia and posteriorly into the parietal lobe. He suffers from a severe nonfluent aphasia and right hemiparesis. His spontaneous speech is restricted to a few stereotyped phrases and he characteristically responds to questions by writing a single word. How-

TABLE 1
EA's Performance on the Boston Diagnostic Aphasia Test (Goodglass & Kaplan, 1983)

Comprehension	
Word discrimination	81%
Body parts	50%
Commands	67%
Complex	58%
Verbal expression	
Nonverbal oral	100%
Verbal agility	100%
Automatic sequence	50%
Word repetition	90%
Phrase repetition	
High	25%
Low	0
Word reading	40%
Responsive naming	40%
Confrontation naming	47%
Animal naming	—
Oral sentence reading	0
Reading	
Symbol/word discrimination	100%
Word recognition	38%
Oral Spelling	0
Word–picture matching	100%
Sentences/paragraphs	60%
Writing	
Mechanics	50%
Recall of writing	98%
Primer level dictation	47%
Written word finding	0
Oral word finding	0
Written naming	90%

Note. Note that performance is expressed in percentage of items correct in each subtest.

ever, he can not orally read the words that he writes. EA's written and verbal productions have been extensively investigated (Mitchum & Berndt, 1994; Shelton & Weinrich, 1997). At the single word level, EA has a mild auditory comprehension deficit, but performs nearly flawlessly on auditory and written lexical decision tasks, can repeat single words without difficulty, and can match words (orally presented and written) to pictures with greater than 70% accuracy. EA's profile on the BDAE (Goodglass & Kaplan, 1983) is presented in Table 1. His performance in naming pictures orally is markedly inferior to his performance in written naming (Table 2). EA fails at orally reading as well as writing nonwords. These results suggest that EA can not support his reading and writing by grapheme-to-phoneme conversion at the single word level.

Training

EA has been extensively trained on C-VIC. The training began with work on the mechanics of the computer interface and retrieval of a small set of nouns. Verbs and sentence structures

TABLE 2
EA's Production of Single Words and Nonwords

	Picture naming			
	Written	Verbal	Reading	Writing to dictation
Noun, high-frequency	26/30 (88%)	11/30 (38%)	12/30 (40%)	6/30 (20%)
Noun, low-frequency	25/30 (83%)	13/30 (43%)	9/30 (30%)	11/30 (36%)
Verb	16/30 (53%)	9/30 (30%)	7/30 (23%)	10/30 (33%)
Nonwords	N/A	N/A	2/55 (4%)	0/55 (0%)

Note. Stimuli consisted of 30 high-frequency nouns, 30 low-frequency nouns, and 30 verbs matched in base and cumulative frequency to the nouns (Frances & Kucera, 1982). Nonwords are matched orthographically to pseudohomophones (Berndt, Haendiges, Mitchum, & Sanson, 1997).

were gradually introduced. Templates and cues were provided to guide the patient and were gradually withdrawn as his performance improved. For each C-VIC construction he produced, he was encouraged to attempt an equivalent verbal response. (See Weinrich et al., 1997, for additional details on the computer interface, training materials, schedules, and protocols.)

For the purposes of this experiment, EA was trained with C-VIC to produce present, past, and future tense morphologies with seven regular and six irregular English verbs. A set of picture stimuli depicting at least four different instances of the thirteen verbs in each of three tenses was developed. EA was required to construct sentences using C-VIC and then to produce the corresponding verbal English sentence. The therapist provided the correct sentence verbally if EA was unable to produce it. No training was conducted in the written modality. EA received two separate episodes of training—the first in 1994 for 3 months and the second from January 1997 to April 1997 (4 months). Training occurred twice per week in hourly sessions. Note that prior to training, his ability to produce tense-marked sentences was quite poor. Further details of training and learning curves are available in Weinrich et al. (1997).

Production of Tense-Marked Sentences

EA's ability to produce tense-marked sentences was assessed with a set of pictures different from those used in training, which included 22 verbs, 12 irregular and 10 regular, each in past present and future. Of the 12 irregular verbs, 6 were verbs that he had received training on, while of the 10 regular verbs he had received training on 4. For each picture, EA was requested to produce an English sentence that described it. Pictures were presented in a randomized order. Verbal responses were recorded and scored off-line. EA was tested in separate sessions on written and C-VIC production.

Productions were scored for (1) production of well-formed, tense-marked sentences with appropriate subjects, objects (for transitive sentences), and verbs with correct inflections and auxiliaries, and correct word order; (2) correct verb root form; and (3) correct tense morphology, which could include the auxiliary, verb inflection, or both. EA's performance on this assessment prior to and after the first training period has been reported previously (Weinrich et al., 1997). For our pre–post evaluation we compared EA's pretreatment data to the first posttraining assessment. However, for further evaluation of his performance with respect to production of past tense morphology we combined EA's performance on six separate administrations after the second training period. His performance remained stable during this period, allowing for the compilation of 60 sentences each with trained verbs in past, present, and future tenses, and 72 sentences with untrained verbs in each tense for the verbal modality. For evaluation of the written production task we combined four sessions administered within the same time period as the verbal production task (n = 264 sentences).

Production of Verb Tense Morphology: Sentence Completion

In order to test EA's verbal and written production of past tense morphology isolated from sentence construction and lexical retrieval, a sentence completion task was designed. Earlier studies had indicated that the semantic and syntactic information contained in sentence completion tasks improved word retrieval for most aphasic patients (McCall, Cox, Shelton, & Weinrich, 1997) and, specifically, EA's writing to dictation (Shelton & Weinrich, 1997). We aimed to elicit only the verb form in the past tense and thus provided him with not only the target verb (in the present progressive) but also a sentence frame that dictated which tense to produce. For example, the experimenter would say ''Today the boy is riding the bicycle. Yesterday the boy ________'' or ''Today the man is painting the wall. Tomorrow the man ________,'' asking EA to complete the second sentence appropriately. Model sentences were of the form Subject–Verb–Object (SVO) or Subject–Verb–Prepositional Phrase (SVPP).

Two blocks of 45 items each (a total of 90 items) were administered in an ABBA design between verbal and written production. The results reflect combined data from two administrations of the same task. An equal number of regular and irregular verbs (counterbalanced among irregular verb classes, Bybee & Slobin, 1982) were included across the two blocks and 10 future tense items were included and dispersed throughout each block. There were 6 regular and 8 irregular verbs from the C-VIC training set included in each block (*drive* was added to the set of trained irregular verbs because EA used it interchangeably with the trained verb *ride*, and *tie* was classed as an irregular verb for written production—it had not been included in the sentence production task.) All verbs were highly imageable verbs according to the MRC database (Coltheart, 1981). Verbs were matched in frequency for the past tense verb forms assessed in the task (rather than base or cumulative forms). Regular and irregular verbs were matched for frequency range (Frances & Kucera, 1982); however, the mean frequency of irregular verbs was somewhat higher than for regular verbs (45.8 for irregular and 39.5 for regular).

When EA indicated that he could not produce the target (e.g., stated ''I don't know'' or fell silent for several seconds) the examiner would repeat the stimulus. If the repetition did not elicit a response, the examiner provided either a phonological (for verbal production) or orthographic (for written production) cue. These cues provided information only about the first phoneme of the target verb. Verbal responses were recorded and scored off-line. False starts, perseverations, and repairs were ignored. After this experiment was completed, the assessment was repeated in a separate session using printed sentences as stimuli. The entire task was administered a second time and the data were combined, since EA responded similarly on both administrations.

RESULTS

Sentence Production

EA's production of fully formed tense-marked sentences improved dramatically after both training periods. Verbal production improved from 15% prior to training to 52% fully correct ($z = 3.838$, $p < .0001$, McNemar's test) after the first training period. Production of correct verb root forms and tense morphology improved from 40 to 80% ($z = 4.811$, $p < .0001$) and 30 to 82% ($z = 6.03$, $p < .00001$), respectively, as illustrated in Fig. 3. Despite significant improvements in production of tense morphology for untrained verbs as compared with data obtained prior to training, EA's production of tense morphology for untrained verbs did not approach his performance for trained verbs, even after the second training period. Across all

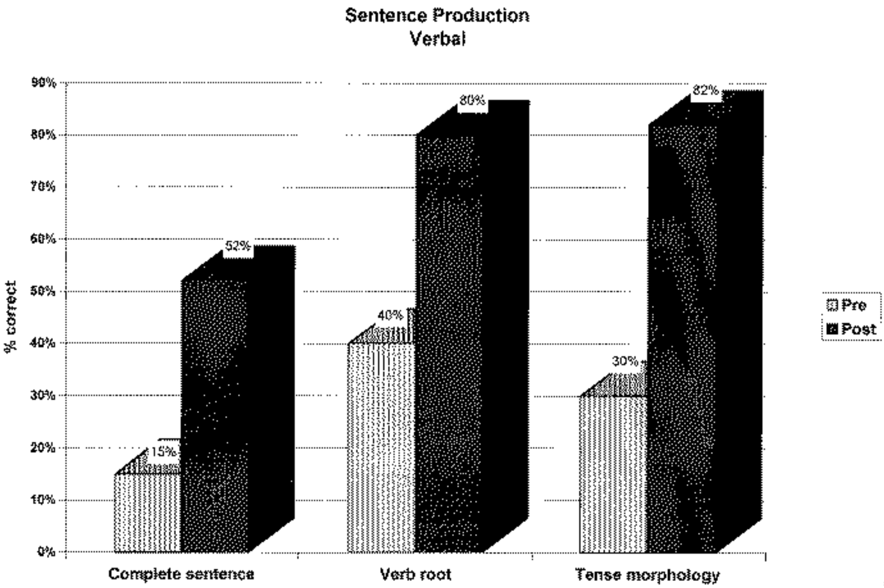

FIG. 3. EA's sentence production in a picture description task prior to and after C-VIC training. Differences between his performance are significant at the $p < .0001$ level.

six administrations, EA produced sentences with trained verbs significantly better than with untrained verbs ($z = 4.17$, $p < .0001$). As demonstrated in Fig. 4, he produced past tense inflection for trained regular verbs significantly better than for untrained regular verbs ($z = 3.13$, $p < .001$) and produced past tense inflection for trained irregular verbs better than for untrained irregular verbs ($z = 4.71$, $p < .001$). In contrast, EA did produce correct auxiliaries for all tenses greater than 69% of the time and without a significant difference between trained and untrained verbs.

Production of written tense-marked sentences improved from 0% fully formed correct sentences prior to training to 73% correct after the first and 76% correct after the second training periods. He produced correct verb root forms at 63% prior to training and at 88% after the second training period ($z = 4.62$, $p < .0001$). In contrast to verbal production, after the second training period, there was no significant difference between his production overall of written sentences with trained and untrained verbs (82% vs. 71%, $z = 1.90$, NS). Past tense inflection for trained regular verbs (92% correct) was not significantly different ($z = 1.0$, NS) from that of untrained regular verbs (75% correct). Untrained irregular verbs were produced with correct inflection at only 25% accuracy as opposed to trained irregular verbs which were produced with correct inflection at 58% accuracy ($z = 2.00$, $p < .05$). The only errors made in the written modality after training were verb substitutions for untrained verbs or regularization of irregular verbs, or combinations of these errors.

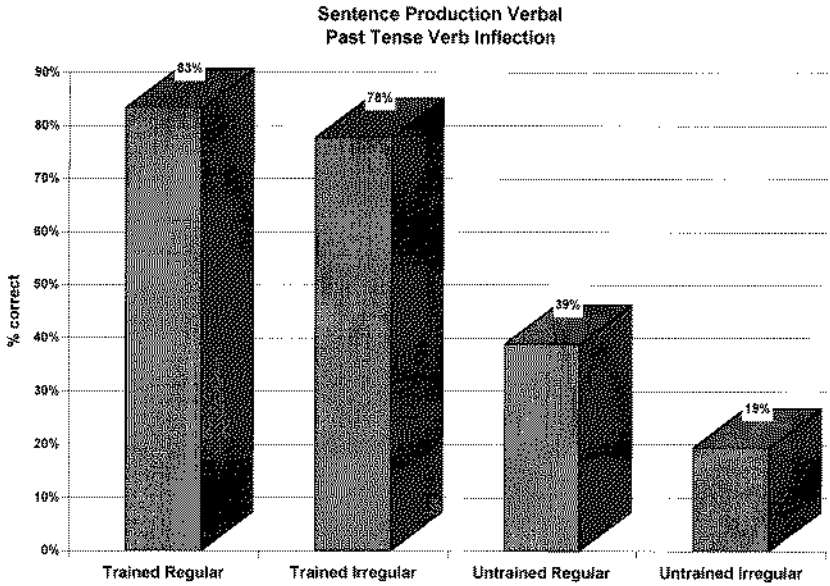

FIG. 4. EA's production of correct verb inflection for past tense in the sentence production task. Note that while he performs well on trained verbs, his production of correct tense morphology on untrained verbs is quite poor.

Sentence Completion

EA's production of inflected verbs across verbal and written modalities in the sentence completion task demonstrated enhanced performance in the trained (although his naturally much weaker) verbal modality for irregular verbs. As shown in Fig. 5a, for verbs on which EA was trained in tense production, there is no significant difference between his performance verbally producing regular and irregular verbs (83% vs. 86%, $z = .37$, NS). However, there is a significant difference between production of verbal and written irregular verb forms (86% vs. 38%, respectively, $z = 2.31$, $p < .02$). On untrained verbs (Fig. 5b), EA performs similarly on regular verbs in both modalities (60% verbal, 66% written, $z = .38$, NS) but demonstrates a nonsignificant trend between his ability to produce written and verbal past irregular verb forms (17% verbal irregular vs. 9% written irregular, $z = .94$, NS). Thus, EA was able to generalize the formation of regular past tense verb forms across modalities, even though he has a profound deficit in phoneme-to-grapheme conversion. Moreover, his generalization of verbal regular verbs was extended to a wide range of phonological forms (/t/, /d/ and /∂d/) even though four of the six regular training verbs were of the /t/ form. There were no significant differences between EA's performances in producing written past tense verbs to printed stimuli and his performance in response to verbally presented stimuli.

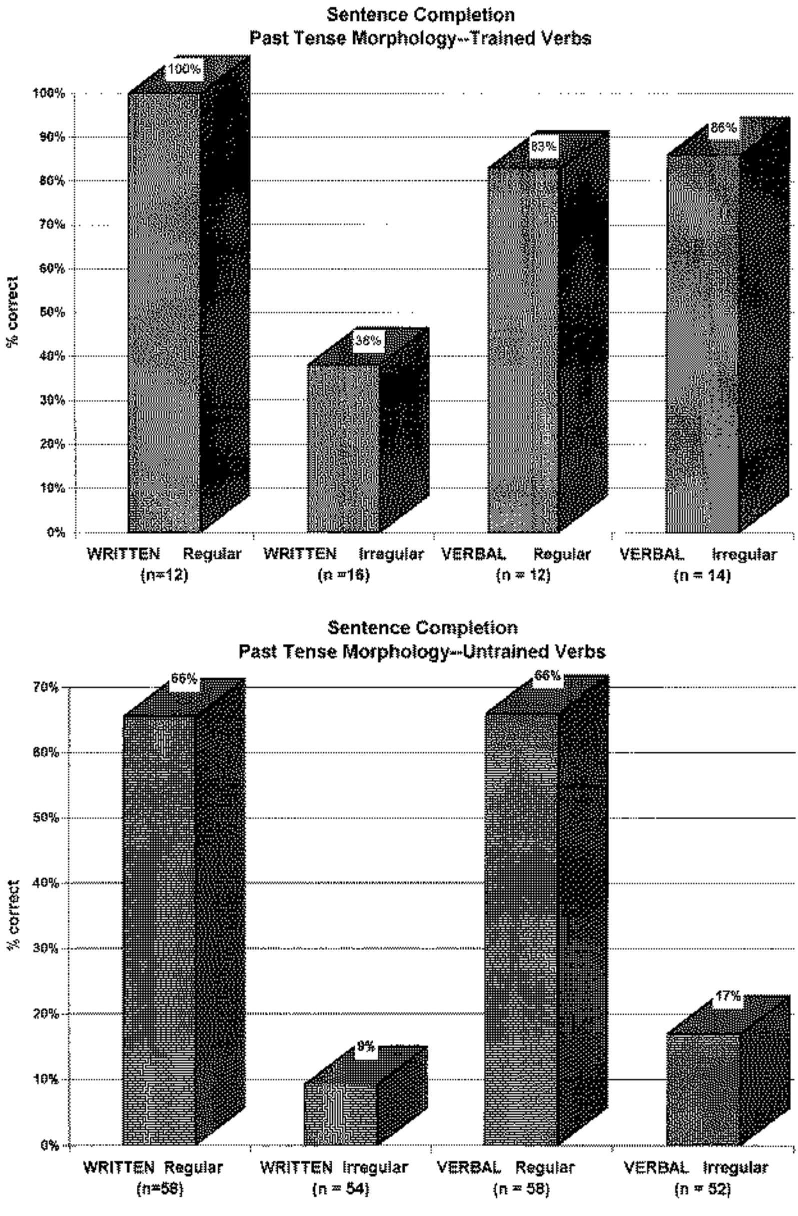

FIG. 5. (a) Sentence completion data for only verbs that had been trained using C-VIC. Note that performance in the untrained (written) modality is comparable for regular verbs but significantly poorer for irregular verbs. The difference between written and verbal irregular verb morphology is significant at $p < .02$. (b) Sentence completion data for only verbs that were *not* trained using C-VIC. Note that regular verbs are produced at comparable rates in both modalities, while irregular verbs are produced much more poorly.

Error data. Incorrect regularization of irregular forms occurred in both modalities for items that were not trained in C-VIC. However, only in the written condition did EA regularize the irregular items (e.g., *sitted, hitted*) that had been trained using the C-VIC-verbal training paradigm. Regularization of irregular past tense forms was greater in the written modality (52%) than in verbal production (30%) ($z = 1.99$, $p < .05$). The greatest number of errors in written irregular verbs arose from regularization.

In the verbal condition, the error pattern is very different. EA never incorrectly *regularized* a trained irregular item (although he missed items by using the wrong verb form). EA incorrectly formed untrained irregulars by producing a phonologically similar response (e.g., *fout* for *fought, load* for *lay, rode* for *read*) or regularized the untrained irregular (e.g., *falled, drawed*). Thus, EA often appeared to show knowledge of the vowel change required even for irregular verbs that he produced incorrectly.

DISCUSSION

Taken together, these data demonstrate generalization of morphosyntactic rules for producing regular verb tense morphology, but also demonstrate the effects of task context upon language performance in aphasic patients. EA's performance in producing complete English past tense-marked sentences, if considered in isolation, would suggest that although he was able to learn to produce these sentences using verbs on which he had received tense training, he could not generalize this training to produce past tense marking on untrained verbs. However, when production of past tense marking is isolated from the tasks of grammatical encoding and lexical retrieval at the sentence level, as in the sentence completion task, it becomes evident that EA can, indeed, produce appropriate past tense marking for untrained regular verbs across both modalities.

The dissociation between EA's production of past tense morphology between spoken and written modalities in the sentence completion task supports the hypothesis that irregular verb inflections are stored as separate, whole entities in the lexicon, while regular verb inflections must be created by the application of a rule (Stemberger, 1995) that operates across modalities, i.e., on representations prior to modality specific output processes. EA was able to generalize production of regular English verb tense morphology to phonologically dissimilar untrained regular forms in the verbal modality. EA also generalized to produce orthographic regular forms in the untrained written modality. He was able to do this despite the nearly complete disconnection that he suffers between the written and phonological production systems (as demonstrated by his extremely poor performance in tasks requiring grapheme-to-phoneme or phoneme-to-grapheme conversion (Shelton & Weinrich, 1997). In contrast, he demonstrated markedly poorer production of trained irregular verb forms in the untrained, written modality than in the trained, verbal modality. The absence of any significant differences between his performance in producing written verb forms with auditory and printed stimuli argues against any explanation based on input processing. Thus, while regular verb tense morphology can be generated by a rule operating on untrained verbs, i.e., verbs that EA has not practiced retrieving, irregular verb tense morphology appears to be stored with verb forms. These data support the observations of Ullman, Corkin, Coppola, Hickok, Growden, Koroshetz, & Pinker (1997), who demonstrated differential production of regular and irregular past tense verb forms between patients with Parkinson's and Alzheimer's diseases. The Parkinsonian patients (and patients with anterior aphasias) produced more errors on regular verbs (requiring rule-based, grammatical processing), while the Alzheimer's patients (and patients with posterior aphasias) produced more errors on irregular verbs (requiring retrieval from memory). A similar dissociation was recently observed in two agrammatic aphasic patients studied in an auditory priming task that contrasted priming in a lexical decision task between regular and irregular verbs (Marslen-Wilson & Tyler, 1997).

Note that, for irregular verbs, tense morphology is stored in modality specific lexical representations. These data are consistent with modality specific repetition priming observed in bilingual speakers (Kirsner, Lalor, & Hird, 1993) and in users of American Sign Language (Hansen & Feldman, 1989). The existence of modality-specific representations explains the poor generalization of treatments for acquired dyslexia to spelling of untreated homophones (Weekes & Coltheart, 1996) and may have implications for design of treatments for developmental language disorders (see Oetting & Horohov, 1997, for a discussion of past tense marking in children with specific language impairment). A modular organization for writing and speaking has also recently been demonstrated in a split-brain patient (Baynes, Eliassen, Lutsep, & Gazzaniga, 1998).

There are several possible candidates to explain the improvements in language production of aphasic patients after C-VIC training. In an earlier report we raised the possibilities that C-VIC training might stabilize ''. . . functional representations by feedback from patients' productions on the computer'' or that C-VIC training focused ''. . . patients' attention on the match between functional information and verb notion stores'' (Weinrich et al., 1997). However, neither of these proposals provides a complete explanation for the data reported here. We have previously argued that successful production of sentences in any modality, including C-VIC communications corresponding to English sentences, implies that patients' functional representations must be intact and would therefore claim that EA is able to construct such representations. Correct verbal production of auxiliaries suggests that he is able to construct at least part of a tense-marked sentence frame at the positional level (Lapointe & Dell, 1989). EA demonstrated correct written tense production (auxiliary and verb inflection) for every regular verb, including the necessary sentential elements, across four post-training administrations of the picture description task, implying intact construction of a grammatical frame for the written modality. Some researchers have proposed that agrammatic patients are unable to integrate semantic and syntactic information (i.e., the mapping hypothesis, see Mitchum & Berndt 1994; Mitchum, Haendiges, & Berndt, 1993; Schwartz, Saffran, Fink, Myers, & Martin, 1994, among others). Given EA's consistent production of well-formed, written, tense-marked sentences with regular verbs, his ability to integrate semantic with syntactic information is unlikely to be impaired.

Hartsuiker and Kolk (1998) recently reported that patients with Broca's aphasia demonstrate enhanced syntactic priming of verbal output, even for relatively syntactically complex sentences, such as passives. They argue that their data provide evidence that the limitations in Broca's aphasic patients' verbal production are attributable to a resource limitation brought about by a temporally constrained processing capacity, since the limitation ''. . . can be overcome by an automatic facilitatory process, syntactic priming.'' Yet, Hartsuiker and Kolk can only demonstrate this facilitation over a short period of time, either directly after the prime or after several intervening items, whereas the improvements in verb production reported here persisted for many months after training.

A third possibility is that C-VIC training improves specific output processing mechanisms. This account would require that phonological and orthographic output representations are independent of each other and of semantic and syntactic information, as recently proposed by Caramazza (1997). The present data extend to sentence production the argument that EA's pattern of performance in producing single words demonstrates an independence between the two output representations (Shelton & Weinrich, 1997). While this account provides a natural way to interpret the differences in EA's performance between the two modalities, it has difficulty in explaining both the speech error data from normal individuals that has motivated the theoretical construct of a functional level sentence representation (Levelt, 1989) and EA's generalization of regular verb tense production across modalities.

Regardless of the theoretical explanation, we have demonstrated that training with an alternative communication interface can result in sustained improvements in some aspects of natural language production and generalization to untrained items and domains. Further investigations are required to determine how to optimize the interface and training and whether these improvements in the laboratory can extend to practical improvements in patients' communicative abilities in every day life outside the laboratory.

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