BRAIN AND LANGUAGE 47, 233–268 (1994)

Pure Alexia: Attempted Rehabilitation and Its Implications for Interpretation of the Deficit

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On the basis of data indicating the failure to encode letters as abstract orthographic identities in a pure alexic patient (D.M.) coupled with hypotheses about the effect of such a failure on word reading, an attempt at changing the nature of letter processing in D.M. was conducted. The training procedures failed to produce any fundamental change in the operations used by D.M. to encode isolated letters or words. However, rapid and massive benefits occurred in the overall speed of reading as a result of the training program. These appear to result from an increased rate of letter identification and the faster integration of individual letters into letter combinations. The observations gathered throughout this rehabilitation attempt provided evidence which constrains the range of possible explanations for the characteristic features of pure alexia. It is proposed that the letter-by-letter reading procedure which is the hallmark of the disorder may follow from an incapacity to directly encode visual letters as abstract orthographic types.

INTRODUCTION

Pure alexia is an acquired reading disorder that normally ensues after a left occipital lesion (Damasio & Damasio, 1983; Greenblatt, 1983) and which dissociates from other linguistic impairments. The time required by patients to identify words is abnormally long and performance seems to depend on the sequential analysis of individual letters (i.e. letter-by-

This research was supported by a post-graduate fellowship from the Medical Research Council (M.R.C.) of Canada to Martin Arguin and by an operating grant from the M.R.C. to Daniel Bub. Thanks to Russ Horowitz for technical assistance. Most important of all, thanks to D.M. for his courage and his assiduous collaboration. Address correspondence and reprint requests to Martin Arguin, Département de psychologie, Université de Montréal, C.P. 6128, Succursale A, Montreal, Québec, Canada H3C 3J7.

0093-934X/94 $6.00

letter reading) rather than on the holistic process that characterizes normal reading. Thus, whereas normal reading speed is barely affected by the number of letters in a word (Forster & Chambers, 1973), each additional letter leads to a dramatic increase of response latency in pure alexics (e.g. Bub & Arguin, 1993; Farah & Wallace, 1991; Patterson & Kay, 1982; Reuter-Lorenz & Brunn, 1991; Warrington & Shallice, 1980).

Nearly all the literature on pure alexia has focused on the nature of the functional impairment responsible for the reading disorder. In contrast, very little longitudinal work has yet been carried out to document the spontaneous evolution of the deficit. Dejerine (1892), who was the first to report the syndrome of pure alexia, studied one patient for a considerable period of time and did not report any notable improvement in his condition over the years. Newcombe and Marshall (1973; Marshall, Newcombe, & Hiorns, 1975; Newcombe, Hiorms & Marshall, 1976; Newcombe, Marshall, Carrivick & Hions, 1974) have reported a marked recovery of word-reading accuracy over an extended period in a patient with left occipital damage, but did not report observations pertaining to reading speed. Friedman and Alexander (1984) indicated that reading speed improved with time in a pure alexic patient they studied over a period of 2 years, although reading remained a laborious chore. No data are presented, however, as the focus of their report lay elsewhere. A better documented report of the evolution of pure alexia is that of Behrmann, Black and Bub (1990). Of particular interest, they examined, over a period of 50 weeks, the progress of their patient, D.S., on word naming and lexical decision times and on the effect of stimulus length in those tasks. Essentially, what they showed is a reduction in word naming and lexical decision latencies as well as a decrease in the effect of stimulus length in those two tasks. Still, response latencies were well above normal and the length effect remained quite large. It therefore appears that, as time progressed, D.S. became more proficient in carrying out the letter-by-letter decoding process she used for reading, but that her reading remained qualitatively unchanged.

These reports indicate that, once they appear, the characteristic features of pure alexia remain qualitatively constant and only quantitative improvements may occur spontaneously. This failure to significantly improve from the massive word recognition disorder that is pure alexia may appear surprising given that the disorder can dissociate from damage to some of the main processing components involved in reading. Thus, in spite of the right homonymous hemianopia that typically accompanies the disorder, a visual shape-encoding deficit does not appear necessary for pure alexia. Evidence congruent with a perceptual encoding impairment has been observed in some cases (Kay & Hanley, 1991; Price & Humphreys, 1992; Rapp & Caramazza, 1991; Reuter-Lorenz & Brunn, 1990) but not in others (Arguin & Bub, 1993a; Warrington & Shallice, 1980). Moreover, in other cases where a shape-encoding deficit was observed and its severity was directly compared with that of the recognition impairment for written stimuli, the former was found to be incommensurate with the latter (Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990). In addition, when they are able to decode letter strings, as they generally are, pure alexics normally show evidence of intact lexical orthographic and phonological knowledge (Patterson, 1981). Thus, regularization errors are not an integral part of pure alexia. In fact, the rare patients who do show this kind of error are considered as belonging to a separate category and have accordingly been labeled letter-by-letter surface alexics (Friedman & Hadley, 1992). As discussed later, however, studies of pure alexia have consistently reported impairments in the functions that seem to mediate the access to lexical–orthographic representations from a perceptual description of the stimulus.

The present article reports a systematic intervention focussing on a particular operation involved in the conversion of a visual to an orthographic code and which attempts to reinstate normal reading in a pure alexic patient, D.M., who has been studied extensively by us (Arguin & Bub, 1993a; Bub & Arguin, 1993). The remediation strategy adopted was motivated by hypotheses, described below, as to the functional architecture of normal reading and the way it has been damaged in pure alexia. To the best of our knowledge, this is the first published report of an attempted rehabilitation of pure alexia. We demonstrate rapid and massive benefits from the training procedures used but no qualitative change in the operations by which the patient reads words. The present study also provides indications about the functional impairment that may be responsible for the deficit.

CASE REPORT AND PRELIMINARY OBSERVATIONS

D.M., born in 1966, was a right-handed undergraduate student in engineering at the time he suffered from a ruptured arterio-venous malformation of the left-posterior cerebral artery in February 1990. Neurosurgery for excision of the malformation was performed in March 1990. Based on the surgical report and CT scans, Fig. 1 illustrates the brain region which was damaged. It may be seen that the area involved corresponds to the lesion typically observed in pure alexics (Damasio & Damasio, 1983; Greenblatt, 1983). D.M. shows no evidence for callosal damage, an observation confirmed by Damasio and Damasio (1983) in a number of cases. D.M.'s main behavioral complaints were of a complete right-homonymous hemianopia, mnestic difficulties, and reading problems. Besides a reading deficit, no evidence for an impairment of other linguistic functions was observed.

Testing at three months post-onset using common words (frequency

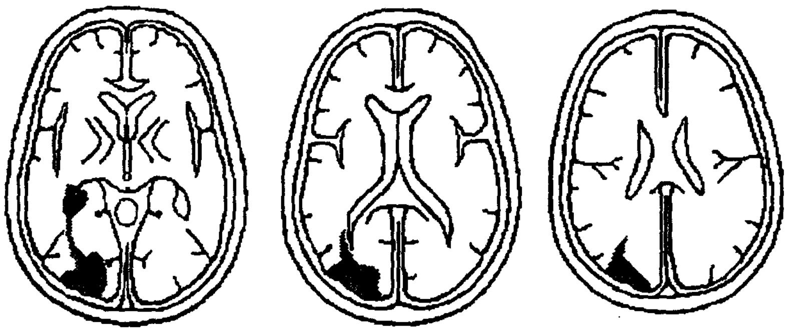

FIG. 1. Location of brain damage in D.M., illustrated by the shaded area. Only the slices on which a lesion was visible on the CT scan are presented.

above 50 per million; Francis & Kucera, 1982) between 3 and 7 letters in length revealed the pattern characteristic of letter-by-letter reading (Fig. 2). Thus, D.M. showed, in addition to extremely long response times (RT's), a linear (r = .99) increase in naming latencies of 420 msec per additional letter in a word. This effect of word length on D.M.'s reading times remained virtually unchanged over the 2 years that followed. This is shown below in the results of the baseline testing that was conducted before the initiation of the rehabilitation attempt.

Prior work with D.M. (Arguin & Bub, 1993a) has shown that his alexia does not follow from an impairment in encoding letter shapes. However, a massive increase in the time required for the *identification* of single letters was observed. A deficit in processing the identity of isolated letters has previously been reported in a number of pure alexic cases but its exact nature has remained unclear (Bub, Black & Howell, 1989; Coltheart, 1981; Farah & Wallace, 1991; Friedman & Alexander, 1984; Friedman & Hadley, 1992; Kay & Hanley, 1991; Kinsbourne & Warrington, 1962; 1963; Levine & Calvanio, 1978; Patterson & Kay, 1982; Reuter-

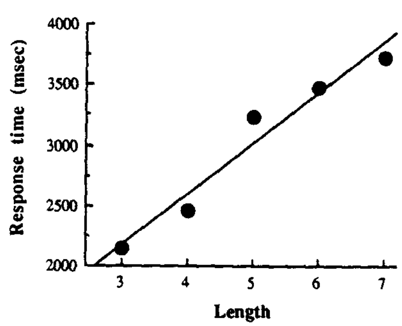

FIG. 2. Effect of word length on D.M.'s naming latency.

Lorenz & Brunn, 1990; Warrington & Shallice, 1980). Nevertheless, on the basis of observations in neurologically intact subjects which indicate that the prior identification of the component letters in a word is required for its recognition (e.g., McClelland, 1976), some authors have proposed that a letter identification deficit may lie at the origin of the word reading impairment in pure alexia (Farah & Wallace, 1991; Friedman & Alexander, 1985; Friedman & Hadley, 1992; Kinsbourne & Warrington, 1962, 1963; Levine & Calvanio, 1978; Reuter-Lorenz & Brunn, 1990).

To further explore the nature of the letter identification impairment in D.M., an experiment that used a letter priming paradigm was conducted. The paradigm was first developed by Jacobs & Grainger (1991) and further extended by us (Arguin & Bub, 1993b). Essentially, a prime, whose relationship with the subsequent target is varied, is displayed for a brief period of time and is followed by a 33-msec pattern mask, and then by the target. One critical aspect of the letter priming data observed in normals (Arguin & Bub, 1993b) relates to the effects of primes nominally identical to the target which were either physically identical (PI; e.g. A-A) or different from it (D/SN, different/same name; e.g. a-A). In a primed explict letter identification task (i.e., letter naming), normals showed, with a prime duration of 150 msec or longer, equal RT benefits from D/SN and PI primes relative to a neutral prime and this was true for each individual subject. This indifference to the physical relationship between prime and target indicates that normal letter identification is based on representations which do not maintain the visual properties of the stimlus. These representations however, are *not* those of *letter names* since it was shown in separate experiments that phonological priming is not a factor in the paradigm used (Arguin & Bub, 1993b). The equivalent benefits with PI and D/SN primes, along with the lack of a phonological priming effect, imply that a set of abstract (neither visual nor phonological) representations are involved in normal letter identification. These abstract representations, which will be called *letter types*, operate over an *orthographic* code.

A primed letter naming experiment was conducted with D.M. in April, 1992. The most important priming conditions were different/same name (D/SN; e.g. a-A), physically identical (PI; e.g. A-A), or neutral (NE, i.e., a blank; e.g. blank-A). Other prime categories were also included, in part so that the prime could not predict the target name, and results in these conditions are of lesser interest. Prime duration was varied between 200 and 500 msec and a 33-msec pattern mask was displayed between the offset of the prime and the onset of the target. To ensure processing of the prime, probe trials occurred on 80 of the 560 trials of the experiment. On these occasions, a question mark was displayed instead of the target and the subject had to report the identity of the prime. D.M. identified the prime correctly on 100% of these probe trials. Relative to a NE prime

(Fig. 3), PI primes resulted in a large reduction of naming times [$F(1, 151) = 28.9$; $p < .001$] whereas D/SN primes had no measurable effect on RT's [$F(1, 151) < 1$].

It is obvious from these results that D.M.'s performance was affected by priming since primes which were physically identical to the target (PI) had a substantial facilitatory effect on letter identification time. In contrast to normal controls however, priming in D.M. was only sensitive to the visual relationship between the prime and the subsequent target. Thus, if the prime was nominally identical to the target but differed from it on its physical aspect (D/SN), no facilitation occurred. This lack of facilitation with D/SN primes cannot be explained simply by D.M.'s increased letter recognition latency, which might have prevented the identification of the prime. Indeed, the patient showed a perfect performance on probe trials, where the identity of the prime had to be reported. This last result unambiguously indicates that the prime durations used here were quite sufficient for D.M. to recognize the prime.

The failure to show D/SN priming in D.M. indicates that, contrary to the normal controls, the lowercase prime presented in this condition contacted a representation that differed from the one upon which the identification of the subsequent uppercase target was based. This implies that the explicit identification of letters in D.M. rests on a representation system that differs from the abstract orthographic code used by normals, possibly due to damage to the access procedures to letter types or to damage to the representations themselves. As indicated above, a letter type code is defined by its indifference to stimulus shape; that is, letter types are abstract and do not represent the visual (or phonological) properties of the items encoded. The lack of D/SN priming suggests that the representation system by which D.M. identifies letters operates over a code that is specific to the visual properties of the stimulus, i.e. what can be called a letter token code.[1] By definition, a letter token representation system is unable, by itself, to integrate the orthographic equivalence of two letters if they have different shapes and therefore cannot support D/SN priming.

These letter priming results emphasize the facts that a number of different codes can be derived in the processing of visual language and that

[1] Throughout the article, we will use the term "token" as meaning a representation of the visual properties of the letters, without implications being made for the exact properties of this kind of representation. However, as suggested by an anonymous reviewer, it is unlikely that this token code is an exact analog of the form of a particular letter. Indeed, as will be shown below, D.M. can produce evidence of recognition of letters printed in rather unusual fonts. Alternative schemes for *visual* representation exist, however. For instance, the token code we are referring to could take the form of a structural description (Marr, 1982), where the visual properties of the object are represented as a set of low-level features and their spatial relations (e.g. a straight vertical line with a dot on top = i).

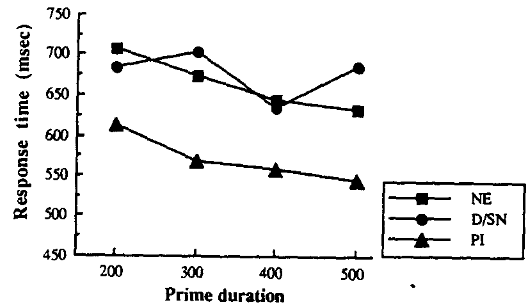

FIG. 3. Letter naming times as a function of priming condition and of prime duration.

identification of written input can proceed in a variety of ways. It is quite clear that an internal visual description of the item—i.e., letter token code—must be derived initially. In normal readers, this letter token code appears to be rapidly and automatically translated into an abstract orthographic code—i.e., letter types—on which overt letter identification has been shown to be primarily reliant (see also Besner, Coltheart & Davelaar, 1984, and Mozer, 1989, for congruent evidence). This conversion of letter tokens to letter types does not seem to occur in D.M., however. It must therefore be assumed that his correct naming of letters involves the access to phonological representations of letter names from letter tokens through some mediation pathway that bypasses the letter type system.

There is reason to believe that this failure to contact a letter-type code for identification may follow directly from D.M.'s cortical lesion (left occipital), the nature of which is common to all pure alexics and which forces the encoding of visual stimulation through the right hemisphere. Marsolek, Kosslyn, and Squire (1992) have studied word repetition priming with lateralized displays in normals. They showed a marked reduction of priming if the case in which items were printed was changed between the study (e.g. WORD) and test (e.g. word) phases with right hemisphere (left visual hemifield) stimulations, but none with presentations to the left hemisphere (right hemifield). Marsolek et al. (1992) concluded from these observations that the right cerebral hemisphere, although quite capable of processing letter shapes, is unable to translate the information into an abstract orthographic (letter type) code; this function would be restricted to the left hemisphere. In agreement with this conclusion, Reuter-Lorenz and Baynes (1992) have tested a callosotomized subject, J.W., in a task comparable to the letter priming experiment reported above. For letter targets presented to either the left or the right hemisphere, large facilitation was observed from primes that were physically identical to the target. However, the identification of an uppercase letter was not facilitated by the prior viewing of its lowercase version if the stimuli were shown to the right hemisphere while benefits from this kind of priming were found with left hemisphere presentations. Again, these results support the view that the right hemisphere is incapable of letter-type encoding. Additional evidence congruent with this hypothesis may also be found in Geffen, Bradshaw & Nettleton (1972) and in Bryden & Allard (1976).

There is also reason to infer that D.M.'s failure to process letters as abstract orthographic units bears a direct relation to his obligation to decode words in a letter-by-letter fashion. The letter priming data reported above indicated that the normal reading system essentially operates on abstract representations of orthographic information (i.e. letter types). In agreement with this view, numerous demonstrations using a variety of paradigms have shown that normal word recognition—i.e., lexical access through a simultaneous processing of the letters in the string—rests on the encoding of letters as abstract orthographic types (Adams, 1979; Besner et al., 1984; Carr, Brown & Charalambous, 1989; Evett & Humphreys, 1981; Humphreys, Evett, & Quinlan, 1990; McClelland, 1976; Mozer, 1989; Paap, Newsome & Noel, 1984; Pollatsek, Well, & Schindler, 1975). Possibly the most striking evidence for this is that, in neurologically intact readers, the processing advantage for words over nonwords is little affected when items are printed in an alternation of upper and lower case letters (e.g. WoRd; McClelland, 1976). The weakness of the effect of the case alternation manipulation on reading also implies that orthographic lexical representations themselves are based on abstract letter identities rather than on letter shapes. It therefore seems that processing of letters at the type level may not reflect only a preference in normal readers, but rather a mandatory operation for the recognition of words as perceptual units. If this is correct, it follows that an incapacity for letter-type encoding should prevent holistic word encoding and force letter-by-letter reading. Support for this hypothesis has been reported by Reuter-Lorenz and Baynes (1992). Thus, in their study of callosotomized patient J.W., they have found that his response times in a lexical decision task were only very weakly affected by stimulus length (in number of letters) when items were presented to the left hemisphere. In contrast, a large increase of response times with stimulus length, suggesting letter-by-letter reading, was observed with right hemisphere presentations. Recall that, in the letter-priming experiment of Reuter-Lorenz and Baynes (1992) with J.W., right hemisphere stimulations also failed to elicit any evidence for the encoding of letters as abstract types.

To summarize, the letter priming data reported above has indicated that D.M. does not base his identification of letters on abstract orthographic representations—letter types—but rather uses letter token representations. In addition, we have shown that this lack of abstract orthographic processing may provide an account for his pure alexia and in particular for its main symptom, namely the word-length effect. Thus, support exists for the hypothesis that the failure of letter type encoding may force

the recognition of words to proceed through the sequential and explicit analysis of their component letters. It therefore appears that if one were able to reestablish a letter type process in D.M., he might be able to develop, with suitable further training of letter strings, a holistic mode of processing for orthographic sequences. In such a case, reading should occur more rapidly and, of greater importance, should be accomplished without the large effect of word length on his reading latency that was reported above (see Fig. 2). Conversely, as long as a letter-type process is not reestablished, our hypothesis predicts that reading will remain letter-by-letter, no matter how rapid letter identification may occur.

TRAINING PROCEDURES AND ASSESSMENT OF BENEFITS

The previous section concluded that letter-by-letter reading in D.M. may follow from his failure to encode letters as abstract orthographic units. Further, it was proposed that if a letter-type process can be reinstated in D.M., this should result in decreased reading latencies and—provided appropriate additional training—in the elimination of the massive word length effect on his reading times.

The initial goal of the training procedures, then, was to bring the subject to spontaneously process letters as abstract types and then to rapidly integrate these letter types into higher-order orthographic units representing letter combinations. To this end, the training tasks, described below, required the identification of both isolated letters and pronounceable letter strings. In each, time pressure for the production of a response was introduced as a way to promote the development of a qualitatively new procedure (i.e. letter type encoding) that would maximize the subject's effectiveness in carrying out the task. In order to determine whether the training effects are specific to the particular stimuli used in the training procedures, these were applied on only one half of the letters of the alphabet, the other half constituting the control set. Assessment of the qualitative and quantitative effects of training was performed by administering a number of experiments at several stages of the rehabilitation program. In each of these experiments, performance with items made of the trained letter set was compared with that of items made of letters of the control set.

METHODS

Training Procedures

As indicated above, the training procedures were only applied on half of the alphabet. The division of the alphabet into the trained and untrained sets obeyed the following criteria: (1) Each letter set included an equal number of vowels (including Y) and consonants. (2) Each set comprised an equal number of letters for which the uppercase and lowercase versions were physically different. (3) A maximum number of words containing only letters from one set or the other exists in English. From these criteria, the trained letter set was made of: A, B, C, G, H, K, L, M, N, O, U, V, and W. The untrained—or control—letter set, which was made of the remaining letters of the alphabet, was never presented in the training tasks.

All of the training tasks and experiments described in this article were run on a Macintosh Plus microcomputer and all responses were given orally and registered by a voice-key. Every trial (except in Exp. 2a) was preceded by a 1500-msec fixation point displayed at the center of the screen. All the stimuli tested were right-aligned at 1 cm to the left of fixation so that items do not fall into D.M.'s blind field (see above).

Same/different letter matching. The first training task was that of speeded same/different comparisons of letter pairs on the basis of their nominal identity (Posner & Mitchell, 1967). Part of the evidence for a deficit in processing letter identities in pure alexia has been obtained from such a task. Thus, some authors have shown that pure alexics are very slow to carry out letter identity matches whereas they are much less affected in performing letter shape matches (Kay & Hanley, 1991; Reuter-Lorenz & Brunn, 1990). Such observations have been interpreted as a deficit in establishing the orthographic equivalence of letters with the same identity but different shapes (e.g., a-A; Reuter-Lorenz & Brunn, 1990).

On each trial, an uppercase letter and a lowercase letter were presented one above the other (distance of 1 cm). D.M.'s task was to indicate as rapidly as possible while avoiding errors, whether the two letters had the same identity (same/different oral response). To prevent that the learning which occurs is only one of pattern matching (i.e. "the *shapes* a and A go together"), each letter was printed in a font randomly selected among a set of fifteen. Some of these fonts were rather unusual but all the letters were readily identifiable. In addition, to maximize the possibility of a change in the process used by D.M. for letter identification (i.e. from letter tokens to types), a response deadline was imposed so that, on some percentage of trials, the deadline was reached before he could make a response. As performance in this task improved (i.e. shorter RT's) the response deadline was made shorter. The response deadline durations used on each training day are presented in Fig. 4, and the percentage of trials when D.M.'s response failed to come before the deadline are shown in Fig. 5. In addition, to promote learning of the identity matches, an auditory feedback (same/different) was provided at the end of each trial. Each block comprised 100 trials (50, "same;" 50, "different").

Overt reading of pronounceable letter strings. The second task was one of speeded naming of pronounceable letter strings. One reason for using this task was the assumption that if holistic processing of letter strings requires that letters are treated as types, then the imposition of time pressure in a letter-by-letter reader may encourage both the use of letter type encoding and the concomitant holistic identification of letters strings. Hence, as in the letter matching task, a response deadline was imposed and was adjusted according to D.M.'s improvements in RT's—the response deadline durations used on each training day are presented below in Fig. 4, and the percentage of trials when D.M.'s response failed to come before the deadline are shown in Fig. 6. More importantly however, the identification (i.e. naming) of pronounceable letter strings was used as a way to train the integration of individual letter identities into higher-order orthographic representations. Indeed, even if we were able to reinstate a letter-type process in D.M., it is not obvious that rapid integration of individual letters into letter combinations should immediately follow. Training of this operation thus appeared necessary.

Pronounceable letter strings were generated by the random juxtaposition of trigrams which appear in more than three words of the English language (e.g., HUC + UCK = HUCK). The use of this kind of item was determined by the need to provide a training experience that is not specific to a particular set of stimuli—i.e. the same words presented over and over again—but that generalizes instead over a wide range of legal English orthographic patterns. Except for the last training day where five-letter strings were used in all

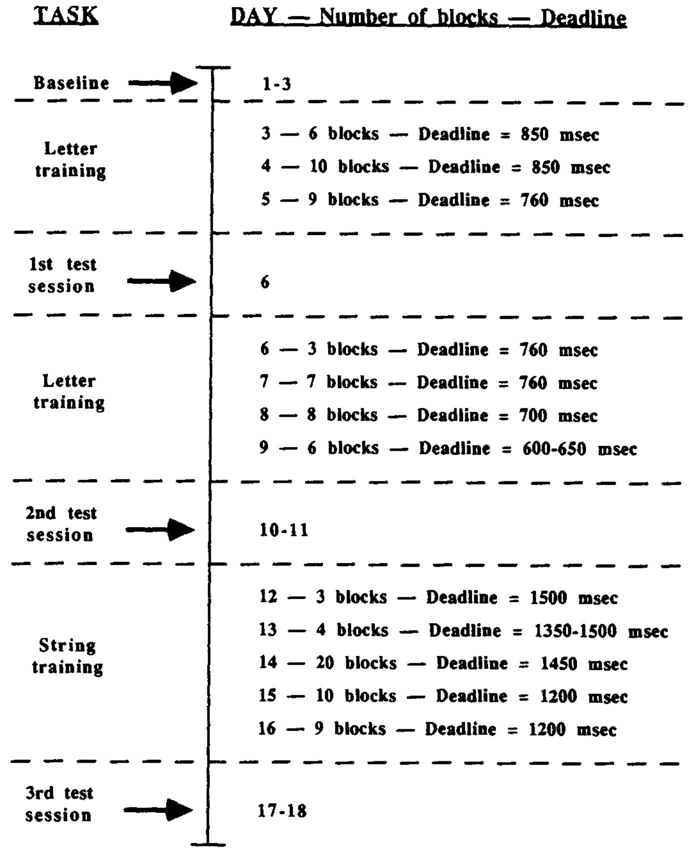

FIG. 4. Time course of events in the rehabilitation program conducted.

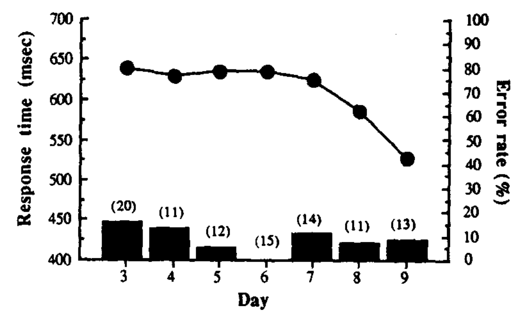

FIG. 5. Performance in the nominal identity letter-matching task (training) as a functic of day. The line graph illustrates average response times and the histogram illustrat average error rates. Numbers above each bar of the histogram indicate the percentage trials when D.M. failed to respond before the deadline.

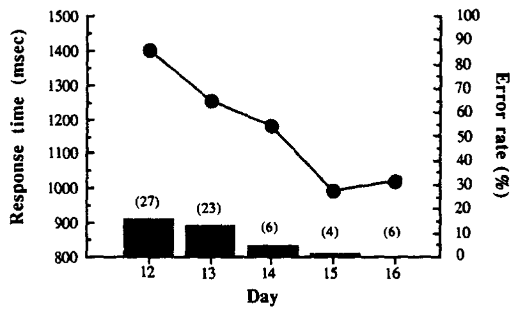

FIG. 6. Performance in the overt naming of legal nonword strings (training) as a function of day. On all days except the last where stimuli were five-letters long, stimulus length was of four letters. The line graph illustrates average response time and the histogram illustrates average error rates. Numbers above each bar of the histogram indicate the percentage of trials when D.M. failed to respond before the deadline.

but one block, stimuli were made of four letters. No list of items was presented more than once to D.M.—i.e. each list he trained upon was a new one. Items were printed in uppercase letters and in a font that resembles script writing. Each block was made of 100 trials.

Experimental Diagnostic Procedures

To assess the effects of training, several experiments were designed, which were administered on a number of occasions during the course of the rehabilitation attempt: baseline, first and second experimental sessions in the course of training, and third experimental session at the end of the rehabilitation program. Two sets of experiments assessed the processing of isolated letters and two others examined the reading of letter strings. Some of these experiments are analogous to the training tasks. They were mainly designed to determine the magnitude of the performance improvements under controlled conditions and to assess the degree to which benefits generalize to letters not presented during training. Other experiments were intended as diagnostics for a qualitative change in the operations used by D.M. to process orthographic stimulation. Of particular interest were questions related to the kind of code—type vs token—upon which D.M.'s letter identification is based and to the presence or absence of a length effect in the overt identification of words. All experiments used stimuli printed in a regular font (Geneva, 24 points). In all experiment, items were segregated as a function of whether they were made of letters from the trained set (A, B, C, G, H, K, L, M, N, O, U, V, and W) or the untrained set (remainder of the alphabet). On each trial conducted, items remained visible until the subject's response.

On a small percentage of trials (over all experiments: 2.4%), the subject's response failed to trigger the voice-key. These trials were not included in the data analyses. The analyses of response times were performed on correct responses only. For these analyses, data points which were further than three standard deviations from the mean in their condition (i.e. outliers) were excluded. One percent of the trials on which a correct response was given were eliminated on this criterion over all the experiments presented here.

Exp. 1: Letter matching. Two letter matching tasks served to assess *quantitative* improvements in the encoding of the shapes and the identities of isolated letters. In the physical matching experiment (Exp. 1a), letters were either both uppercase or both lowercase and the task was to indicate orally by a "same"/"different" response whether the letters were physically identical. In the nominal matching experiment (Exp. 1b), one letter was upper-

case and the other lowercase and D.M. had to indicate whether the items were nominally identical. Responses were to be given as rapidly as possible while avoiding errors.

For both experiments, the items used from the trained set were: A, B, G, H, M, and N and from the untrained set: D, E, J, Q, R, and T. This selection was determined by the fact that these letters are physically rather different between their uppercase and lowercase versions (based on the confusion matrix of Boles & Clifford, 1989). This insures that responses in Exp. 1b were based on a judgment of the nominal identity of the letter pairs rather than on their shapes. Each experiment was made of 100 trials, run in a single block. Half of the trials were "same," and half were "different." An equal number of trials was run in each condition with items from the trained and untrained sets.

A reduction of RT's in Exp. 1b may imply a faster retrieval of letter identities only if the performance improvement is notably larger in the nominal than in the physical matching task. In addition, an increased rate of letter identification need not reflect the development of rapid visual access to abstract orthographic identities. Rather, qualitatively different operations may be available for the execution of nominal matches on letter pairs. In particular, it was noted above that D.M.'s letter naming performance may be mediated by a pathway that permits access to letter names from visual tokens, while bypassing the letter type system. In the same way, nominal matching may be performed on the basis of a letter name code and faster access to these phonological representations would imply shorter nominal matching latencies. Exp. 2 (see below) will serve to determine whether the training program has succeeded in actually reinstating letter type encoding in D.M.

Exp. 2: Letter priming. Two letter priming experiments were designed to assess *qualitative* changes in the kind of representations used by D.M. to identify isolated letters. Exp. 2a used a letter priming paradigm similar to that described previously (masked priming). A checkerboard with sides of 1 cm served as masking stimulus and as fixation point and was shown for 1500 msec at the center of the display screen at the beginning of each trial. It was followed immediately by a priming stimulus shown in the same location for a duration of 200 msec. The masking stimulus was then presented again for a duration of 33 msec, followed immediately by the target letter. An analogous letter priming experiment (flank priming; Exp. 2b), where two identical versions of the prime were shown, 1 cm above and below the target location, was also used. In this experiment, the target was presented 200 msec following the onset of the prime.

In both experiments, the subject's task was to name the target as rapidly as possible while avoiding errors. Targets were uppercase letters and three main categories of primes were used: neutral (NE, which was an asterisk; e.g., *-A), different/same name (D/SN; e.g. a-A), and physically identical (PI; e.g. A-A). In addition, filler primes (FILL), which bore no relationship to the subsequent target, were used on 25% of the trials so that letter primes in the other conditions could not serve to predict the target name. Except for trials with D/SN primes, targets were chosen randomly among the letters from the trained or untrained sets and the prime was chosen according to the condition. The PI and FILL primes were printed in uppercase. D/SN primes were printed in lowercase and the targets that could be used in this condition were restricted to A, B, G, H, M, and N for the trained set and to D, E, J, Q, R, and T for the untrained set. This restriction was necessary to insure that primes and targets were physically different from one another in the D/SN condition (Boles & Clifford, 1989). Each experiment comprised 200 trials that were run in a single block. Twenty five trials were run in each condition (i.e. priming condition × letter set).

In the event that the training program succeeds in reinstating letter type encoding in D.M., a large facilitatory effect of D/SN primes should occur in Exps. 2a and 2b. In addition, the magnitude of this facilitation should be comparable to that occurring with PI primes, as previously obvserved in normal readers (Arguin & Bub, 1993b).

Exp. 3: Four-letter string reading. A set of experiments served to quantify the improvement in the time required by D.M. to read letter strings. Items were four-letter words and pseudowords which were to be read as rapidly as possible. Sets of stimuli made of letters from the trained and untrained sets were matched on their frequency of occurrence in the English language (Francis & Kucera, 1982). Pseudowords were made by changing one letter in a real word and were matched to the words used on bigram frequency (Mayzner & Tresselt, 1965). In Exp. 3a, all items were printed in uppercase, whereas in Exp. 3b items were printed in an alternation of upper and lowercase letters. This case alternation manipulation in Exp. 3b was performed especially to analyze whether the benefits that may result from the training on the overt reading of letter strings occurs over letter *token* combinations or over letter-*type* combinations. Exp. 3a was run on the baseline, second and third experimental sessions, and Exp. 3b was run only on the third session.

An error was made in the initial construction of the stimulus list, so that some items contained letters from both the trained and untrained sets. This list was run on the baseline and second experimental sessions. The items which comprised letters from both sets were not included in the analyses of the data from these sessions. The condition containing the highest number of trials in these analyses was words/trained, with 76 items, and the condition containing the lowest number of items was words/untrained, with 53 items. Corrections were made afterwards so that items used in the third experimental session respected the division between trained and untrained letter sets. The corrected list contained 60 items in each condition (i.e. word/nonword × letter set).

It should be noted that a significant reduction of D.M.'s response times as a result of training in Exps. 3a and 3b need not imply a qualitative change in his reading procedure. That is, response latencies may become considerably shorter even if reading remains letter-by-letter.

Exp. 4: Word length effect. The last set of experiments was designed to examine changes in the effect of word length on reading times. If there is a genuine relationship between the process on which letter identification is based and the occurrence of a word length effect in pure alexia, reestablishing the abstract encoding of letters as orthographic types in D.M. would imply the absence of any major effect of word length. In contrast, if the rehabilitation procedures fail to reinstate letter type encoding, it follows that word length should remain a critical determinant of reading speed.

The subject's task was to read the target aloud as rapidly as possible while avoiding errors. The words used were three, four, five, or six letters in length. In Exp. 4a, words were printed in uppercase letters. In Exp. 4b, a case alternation manipulation like that in Exp. 3b was used. Exp. 4a was run on the baseline, second and third experimental sessions, and Exp. 4b was run only on the third session. Words made of letters from the trained and untrained sets that were of the same length were matched on their frequency of occurrence in the English language (Francis & Kucera, 1982).

As for Exp. 3, an error was made in the initial construction of the stimulus list, so that some items contained letters from both the trained and untrained sets. This list was run on the baseline and second experimental sessions. The items which comprised letters from both sets were not included in the analyses of the data from these sessions. Between six (in two conditions) and 15 trials remained in each condition after the improper items were removed. A corrected list which respected the division between trained and untrained letter sets was constructed for the third experimental session. This list contained 20 trials per condition.

Chronology of Events

Figure 4 illustrates the chronology of events that occurred in our attempt to reinstate normal reading in D.M. A baseline was established on Days 1–3 on all the experiments

described above, except for Exps. 3b and 4b which were only conducted at the end of the rehabilitation program. On Days 3–5, blocks of letter training were administered. On Day 6, the four tests focusing on letter processing (i.e. letter matching and letter priming) were administered once more. Letter training continued on Days 6–9. On Days 10 and 11, an experimental session assessed the processing of both isolated letters and orthographic strings. Then, from Days 12 to 16, training on pronounceable letter strings occurred. A final experimental session was conducted on Days 17 and 18 involving all of the experiments described above. At that time, our rehabilitation attempt was interrupted by D.M.'s obligation to leave Montreal. The work reported has been conducted in May, 1992.

RESULTS AND DISCUSSION

Training Procedures

Same/different letter matching. Figure 5 shows the average correct RT's and error rates on the letter matching training for each day on which it has been conducted. Whereas there was no systematic pattern of evolution on error rates in this task, remarkable progress occurred on the RT measure. Thus, on the first day of training, the average RT over the six blocks that were administered was of 640 msec. RT's remained quite stable for the following four days. However, on Days 8 and 9, a substantial performance improvement occurred, with average RT's of 587 and of 527 msec, respectively. In summary, a reduction of 18% of the RT's for nominal identity matching of letter pairs occurred over a period of 7 days. It is clear than that D.M. improved his capacity to perform nominal identity matches of isolated letters with practice. The experiments designed to assess the effects of the training program will provide clues with respect to the nature of the change which occurred in the process involved in this task.

Overt reading of letter strings. Progress on the string training task is illustrated in Fig. 6. Rapid and dramatic improvement occurred on the RT measure, with an initial average RT of 1400 msec with four-letter strings and an average latency of 1020 msec with five-letter strings on the last training day (Day 16)—this is the only day in which training with five-letter items occurred. The block of four-letter items that was administered on the fifth string-training day gave an average RT of 860 msec. If only the data for four-letter strings are considered, the training procedure resulted in a 39% reduction of RT's over a period of 5 days. A notable improvement on the error rate measure can also be observed over the training period. Then, as was the case with nominal matching of letters, a dramatic improvement of reading speed for short letter strings occurred with practice. Again, indications as to the origin of this performance improvement are provided by the results of the experiments, which are described below.

Experimental Diagnostic Procedures

Exp. 1: Letter matching. Figure 7 illustrates the average correct RT's for each experimental session in the physical (Exp. 1a) and nominal identity (Exp. 1b) matching tasks. Corresponding error rates are presented in Table 1. The correct RT's in each task were analyzed separately with ANOVA's that included three factors: session (baseline, 1st, 2nd, or 3rd), letter set (trained or untrained), and response (same or different). Error rates in each task were analyzed separately for the trained and untrained letter sets with a χ^2 procedure (this statistical test can only handle two-way designs so the data set was split according to the letter set factor; the same procedure was done in the following experiments). The correlations between RT's and error rates were of 0.17 (*n.s.*) and of $-.34$ (*n.s.*) for the physical and name identity matching tasks, respectively, indicating no speed-accuracy trade-off.

To briefly summarize, the data analyses presented below indicated, in the two letter-matching tasks, a reduction of RT's as the training program progressed. This reduction was rather weak in physical matching but

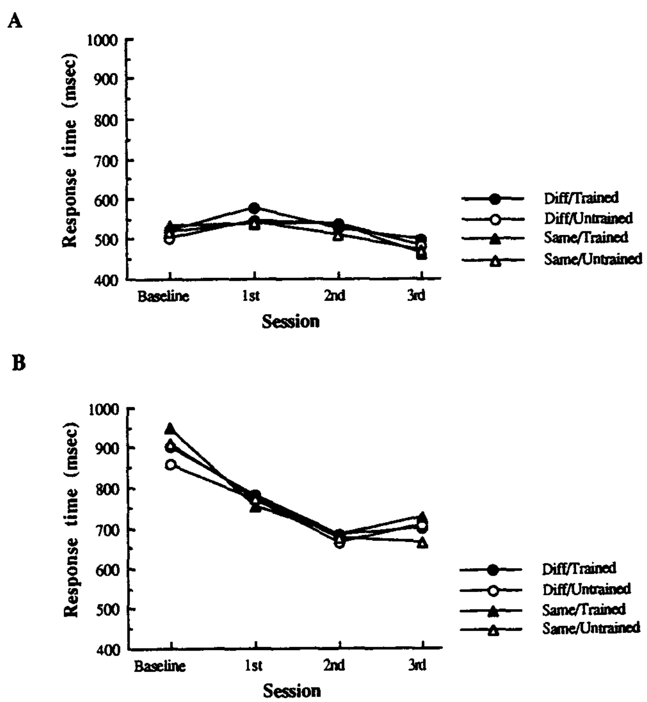

FIG. 7. (A) Average RT's for each condition of the physical matching of letter pairs experiment (Exp. 1a) on each experimental session. (B) Average RT's for each condition of the nominal matching of letter pairs experiment (Exp. 1b) on each experimental session.

TABLE 1
Error Rates (%) Observed in Each Condition and in Each Experimental Session in the Physical (Exp. 1a) and Nominal Identity (Exp. 1b) Letter-Matching Experiments

Experiment	Session	Same trained	Same untrained	Different trained	Different untrained
Phys. match	Baseline	.0	.0	12.0	.0
	1st	.0	4.2	.0	.0
	2nd	4.0	4.0	4.0	4.0
	3rd	.0	.0	.0	.0
Name match	Baseline	.0	.0	.0	.0
	1st	8.0	4.0	12.0	.0
	2nd	4.0	8.0	12.0	4.0
	3rd	.0	.0	.0	.0

much larger in nominal matching. Neither of the experiments indicated any difference in performance between letters from the trained and untrained sets, thus showing that the effect of training on the processing of individual letters was not specific to the items used. It rather appears that training affected a general procedure involved in the identification of any letter that is shown in isolation.

For the physical matching experiment, the analysis of variance applied on RT's only indicated a moderate effect of session [$F(3, 371) = 15.8$; $p < .001$], but no other main effect or interaction. The session effect indicates a tendency for RT's to decrease from the baseline to the third experimental session. Thus, overall, RT's went from 525 msec in the baseline assessment to 478 msec in the third test session, an improvement of 9%. The χ^2 analysis applied on error rates showed no significant effect for either the trained [$\chi^2(3) = 1.9$; *n.s.*] or the untrained [$\chi^2(3) = .7$; *n.s.*] letter sets.

The ANOVA applied on the RT's observed in the nominal identity matching experiment again showed a main effect of session [$F(3, 346) = 54.3$; $p < .001$], but no other main effect or interaction. The main effect of session consists in a large reduction of RT's as sessions progressed. From the baseline session, where the average RT was of 905 msec, to the last experimental session, which gave an average RT of 698 msec, performance improvement was of 23%. This is mainly apparent in the reduction of RT's from the baseline to the second experimental session. No significant effect of condition was found on error rates with the trained [$\chi^2(3) = .2$; *n.s.*] or untrained [$\chi^2(3) = .6$; *n.s.*] letter sets.

The training procedures used here had only a weak effect on D.M.'s performance in the physical matching of isolated letters. Quite possibly, one could expect, with practice, an improvement of comparable magnitude in a normal observer. The reduction of RTs for nominal identity matching however is quite substantial. The contrast between D.M.'s results in the physical and nominal matching tasks indicates that his improvement in the latter does not follow from the faster encoding of letter shapes. It rather suggests that it is the retrieval of letter identity which became much more efficient with training. It should be noted however that this increased rate of letter identification is not specific to the letter set that was trained. Thus, in the data analysis of Exp. 1b, no main effect or interaction involving the factor of letter set was observed. In addition, Fig. 7b provides no indication for a trend toward larger benefits from practice with the trained letter set.

The large reduction in the time required by D.M. to perform identity matches of isolated letters indicates that training improved his capacity to transcode the shape of individual letters into a representation of their identity, and this occurred whether they are from the trained set or not. The letter priming experiments described below will allow us to determine whether this improvement in letter identification follows from the processing of letters as abstract orthographic units.

Exp. 2: Letter priming. Experiment 1 confirmed that the rehabilitation program improved D.M.'s rate of letter identification. In Exp. 2, the letter priming paradigm served as a diagnostic for a change in the kind of representation he uses for letter identification. In particular, we were interested in contrasting between letter identification which is based on token (i.e. shape specific) and type (i.e. orthographic) codes.

The average correct RT's observed in each of the letter priming experiments are shown in Fig. 8. Error rates in these experiments are presented in Table 2. Analyses of variance were applied on the RT data. Factors were: session (baseline, 1st, 2nd, or 3rd), letter set (trained or untrained), and priming condition (NE, D/SN, or PI). Error rates in each experiment were analyzed with χ^2s. Correlations between RT's and error rates were not significant (masked primes: $r = -.19$, *n.s.*; flank primes: $r = .03$, *n.s.*), thus indicating the absence of a speed-accuracy trade-off.

In summary, the data analyses showed, as a result of training, an improved rate of letter identification. As for Exp. 1b, this result occurred with the letters from both the trained and untrained sets. No change in the pattern of priming effects was observed however. Weak facilitation relative to neutral primes was seen with D/SN primes whereas PI primes resulted in a major reduction of RTs. This result did not vary as a function of either experimental session or letter set.

For the masked priming experiment (Exp. 2a), the ANOVA applied on the correct RT's only showed a main effect of priming condition [$F(2, 554) = 115.5$; $p < .001$] and a marginally significant effect of session [$F(3, 554) = 2.3$; $p < .08$]. No other main effect or interaction was significant. Pairwise comparisons on the effect of priming indicated that RT's with NE primes were longer than with D/SN [$t(554) = 5.9$; $p < .001$] and PI primes [$t(554) = 15.1$; $p < .001$]. The marginal effect of

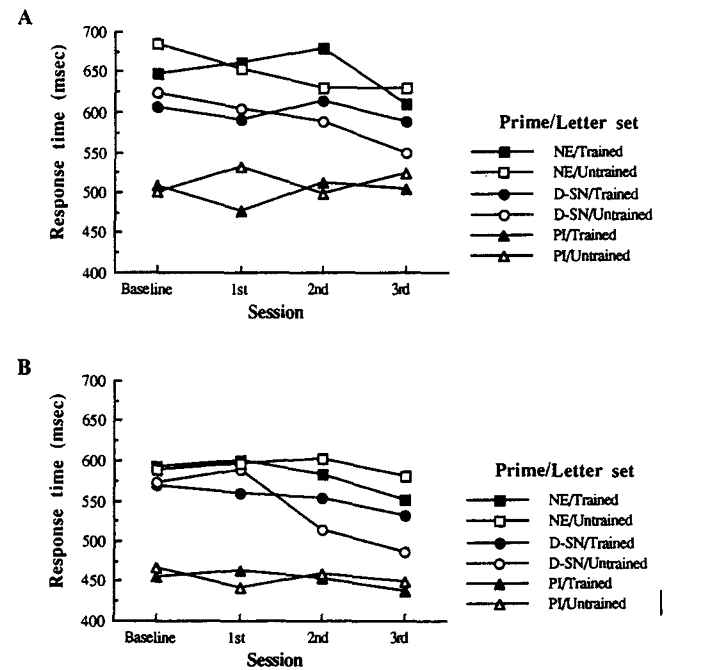

FIG. 8. Average RT's for each condition of the letter priming experiments on each experimental session. A) Masked primes (Exp. 2a). B) Flank primes (Exp. 2b).

session suggests a trend for a reduction in RT's as sessions progressed. The χ^2 analysis applied on error rates revealed no significant effect for either the trained [$\chi^2(6) = 4.1$; *n.s.*] or the untrained [$\chi^2(6) = 4.0$; *n.s.*] letter sets.

The results in the flank primes experiment (Exp. 2b) were quite similar to those observed with masked primes. The analysis of RT's revealed

TABLE 2
Error Rates (%) Observed in Each Condition and in Each Experimental Session in the Masked (Exp. 2a) and Flank (Exp. 2b) Letter-Priming Experiments

Experiment	Session	NE trained	NE untrained	D/SN trained	D/SN untrained	PI trained	PI untrained
Masked	Baseline	.0	.0	.0	.0	4.0	.0
	1st	.0	.0	.0	.0	.0	.0
	2nd	.0	3.8	8.0	.0	.0	4.3
	3rd	.0	.0	4.2	4.0	.0	4.0
Flank	Baseline	.0	3.8	4.0	.0	8.0	.0
	1st	.0	.0	.0	.0	.0	.0
	2nd	4.2	3.8	.0	.0	.0	.0
	3rd	4.2	.0	.0	.0	.0	4.0

main effects of session [$F(3, 555) = 4.7$; $p < .005$] and of priming condition [$F(2, 555) = 106.9$; $p < .001$]. No other main effect or interaction was significant. The main effect of session indicates a reduction of RT's from the baseline to the third experiment session. Pairwise comparisons on the effect of priming showed longer RT's with NE primes than with D/SN [$t(555) = 4.3$; $p < .001$] and PI primes [$t(555) = 14.3$; $p < .001$]. The analysis of error rates showed no significant effect for either the trained [$\chi^2(6) = 5.1$; *n.s.*] or the untrained [$\chi^2(6) = 2.9$; *n.s.*] letter sets.

One aspect of the letter priming results which should be discussed first is that D.M.'s response latencies with both D/SN and PI primes were shorter than NE primes. This is at variance with the preliminary letter priming experiment which had been conducted earlier, where only PI primes led to shorter RTs than NE primes. The facilitatory effect of D/SN primes in Exps. 2a and 2b cannot be taken as good evidence that D.M. now processes letters as abstract types, however. Indeed, a large difference still remains between his RT's with D/SN (average RT's of 596 msec and of 546 msec in Exps. 2a and 2b, respectively) and PI primes (average RT's of 506 msec of 452 msec in Exps. 2a and 2b, respectively). In contrast, normals, who do process letters as types in a naming task, show similar RT's with D/SN and PI primes even with a shorter prime duration than that used here (Arguin & Bub, 1993b). Moreover, some compromise had to be made in our choice of letters tested in the D/SN condition in order to have a sufficient variety of items. Thus, some of them were not as structurally different with respect to their lowercase and uppercase versions as we would ideally want. In particular, in the items from the trained set, the letters h-H and m-M were used, and in the items from the untrained set, we used the letters j-J and t-T. According to the Boles & Clifford (1989) cross-case confusion matrix, these letters have a somewhat higher degree of similarity between their lower and uppercase versions than the letters originally used in the initial letter priming experiment reported above as well as with normal subjects (Arguin & Bub, 1993b). The weak benefits from D/SN primes showed by D.M. may, at least in part, result from the physical similarity of these primes with the subsequent target.

The most notable finding from Exps. 2a and 2b is that the training procedures failed to change in any significant way the pattern of D.M.'s letter priming effects. Thus, with both masked and flank primes, the results did not show any significant interaction of priming condition with either the factors of session or training set. Nevertheless, D.M.'s reduction in letter naming time as sessions progressed indicates, as did Exp. 1b, that training improved his capacity to retrieve the identity of individual letters from both the trained and untrained sets. As discussed above, it does not appear that D.M.'s improved rate of letter identification can be attributed to an encoding of letter identities as abstract types. The available evidence rather suggests that the only change which occurred is quantitative and therefore that his letter identification still rests on letter token representations.

Exp. 3: Four-letter string reading. Results from the training sessions provided indications for a marked reduction of reading latencies for letter strings in D.M. Exp. 3a mainly served to assess the magnitude of this improvement under controlled conditions. Exp. 3b was conducted in order to allow some specification of the aspect of orthographic processing which was affected by examining the effect of case alternation.

The outcome of the data analyses reported below showed three principal results: (1) Training led to a non-specific reduction of RT's for items made of letters from both the trained and untrained sets. (2) On the last experimental session, an additional reduction of RTs was observed for "trained" items relative to "untrained" ones. This added benefit specific for words and nonwords made of letters from the trained set was resistant to case alternation. (3) Whereas shorter RTs were observed for words than for nonwords in the baseline and second experimental sessions, the result of the last session suggest a reduction of this lexicality effect.

Average correct RT's for each session when reading of four-letter uppercase words and nonwords was tested (Exp. 3a) are illustrated in Fig. 9A. Corresponding error rates are shown in Table 3, Exp. 3a. The correlation between RT's and error rates was null ($r = .00$; *n.s.*), thus showing the absence of a speed-accuracy trade-off. The analysis of variance applied on the RTs included the following factors: session (baseline, 2nd, or 3rd), letter set (trained or untrained), and lexicality (word or nonword). Results showed main effects of session [$F(2, 656) = 204.8$; $p < .001$], letter set [$F(1, 656) = 14.6$; $p < .001$], and lexicality [$F(1, 656) = 61.4$; $p < .001$]. These main effects indicated that RTs decreased as testing sessions progressed, that RTs were shorter with items made from letters in the trained set than in the untrained set, and that RTs were shorter with words than with nonwords. In addition, significant two-way interactions of session × lexicality [$F(2, 656) = 20.8$; $p < .001$] and of session × letter set [$F(2, 656) = 11.6$; $p < .001$] were found. Analysis of the simple effects of the session × lexicality interaction showed that RT's were shorter with words than with nonwords in the baseline [$F(1, 656) = 91.2$; $p < .001$] and the second [$F(1, 656) = 13.0$; $p < .001$] experimental sessions, but that lexicality had no effect in the third testing session [$F(1, 656) < 1$]. Detailed analysis of the session × letter set interaction revealed no difference between items made of letters in the trained and untrained sets in the baseline [$F(1, 656) < 1$] and second sessions [$F(1, 656) < 1$], but shorter RTs for trained items in the third experimental session [$F(1, 656) = 36.3$; $p < .001$]. The χ^2 analyses applied on the error rates showed no significant effects [trained: $\chi^2(2) = 1.51$ *n.s.;* untrained: $\chi^2(2) = 2.2$; *n.s.*;].

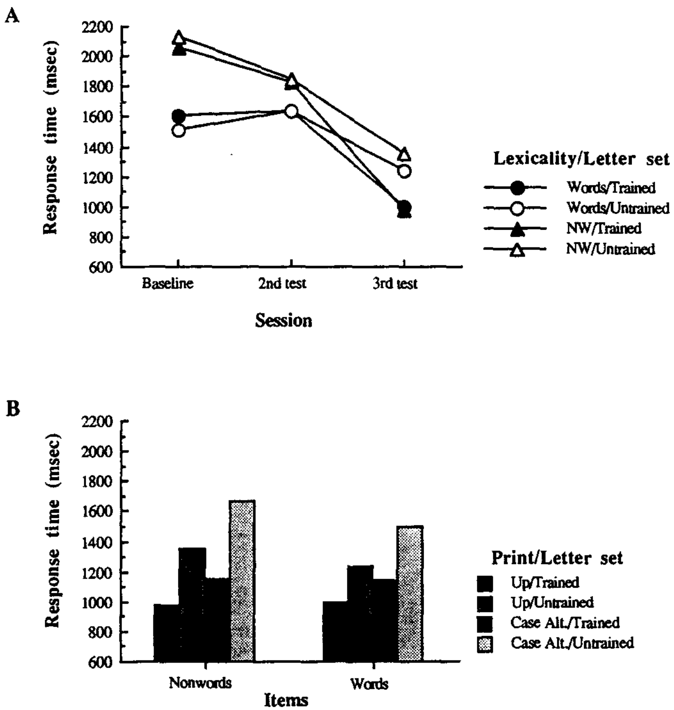

FIG. 9. (A) Average response latencies in the naming of four-letter words and nonwords (Exp. 3a) on each experimental session where the experiment was conducted. (B) Average response latencies in the naming of four-letter words and nonwords printed in uppercase or case alternated formats (Exp. 3b).

TABLE 3
Error Rates (%) Observed in the Experiments Involving the Reading of Four-Letter Strings (Exps. 3a and 3b)

Session	Words trained	Words untrained	Nonwords trained	Nonwords untrained
		Exp. 3a		
Baseline	9.2	11.3	11.3	7.5
2nd	4.1	3.8	5.4	11.5
3rd	11.9	9.0	4.5	10.9
		Exp. 3b		
Uppercase	11.9	9.0	4.5	10.9
Case alt.	12.5	7.6	16.2	13.6

On the third session, an additional experiment (Exp. 3b) where four-letter words and nonwords were printed in a case alternated format (e.g. WoRd) was conducted. The effect of this manipulation will help in specifying the kind of operation that was affected by training and which is responsible for the greater performance improvement for the trained items in the third experimental session that was seen in Exp. 3a. Results from this experiment were compared to those observed in D.M. with four-letter uppercase strings in the third testing session. The average RTs are shown in Fig. 9B and the corresponding error rates are presented in Table 3, Experiment 3b. The correlation between RT's and error rates was positive and nonsignificant ($r = .18$; *n.s.*), indicating that no speed-accuracy trade-off occurred. The ANOVA applied on the correct RT's indicated main effects of the letter set from which the items were made [$F(1, 457) = 256.7$; $p < .001$], of the lexicality of the items [$F(1, 457) = 10.0$; $p < .005$], and of the case alternation manipulation [$F(1, 457) = 95.3$; $p < .001$]. Thus, RTs were shorter with items made of the trained letter set than of the untrained one, with words than with nonwords, and with items printed in uppercase than with items printed in a case alternated format. Also, significant two-way interactions of letter set × case alternation [$F1, 457) = 7.3$; $p < .01$] and of letter set × lexicality [$F(1, 457) = 9.2$; $p < .005$] were seen. Simple effects of the two way interactions revealed significant effects of letter set with both uppercase [$F(1, 457) = 91.6$; $p < .001$] and case alternated [$F(1, 457) = 172.8$; $p < .001$] items, and with both words [$F(1, 457) = 85.4$; $p < .001$] and nonwords [$F(1, 457) = 180.83$; $p < .001$]. It may be seen in Fig. 9B however, that the effect of letter set is larger with nonwords than with words and larger with case alternated items than with uppercase ones. The analysis of error rates showed no significant effect [trained: $\chi^2(1) = .2$; *n.s.*; untrained: $\chi^2(1) = .2$; *n.s.*].

The results observed in experiments that required D.M. to read four-letter strings contrast markedly with those reported previously on the processing of isolated letters in that benefits specific to the trained letter set were observed here. Indeed, on the third testing session, words and nonwords made of letters from the trained set were read markedly faster than those made of letters from the untrained set. This difference may be attributed solely to the training which was conducted for the processing of letter strings. Thus, on the second experimental session, which occurred after the termination of training on isolated letters and before the start of string training (see Fig. 4), no indication of a RT difference is seen between items of the trained and untrained sets (Fig. 9A).

One important feature of the present results is that the reduction of RT's for items in the trained set was resistant to a change in the visual format in which the letter strings were printed. Thus, printing items in a case alternated format did not reduce—but rather increased—the magnitude of the RT difference between items from the trained and untrained sets (Fig. 9B). What this suggests is that the system which is responsible for the letter set effect operates on a nonvisual code (i.e. where the particular shapes of the items are not represented; e.g. phonological or orthographic codes) corresponding to the identity of written material. Indeed, training was conducted only with items printed in uppercase letters. Had the training effect been specific to visual format, no additional benefits for items made of letters in the trained set should have occurred with strings printed in a case alternated format.

Four points allow to specify more precisely the locus that was affected by the training procedure and which leads to shorter RTs for items of the trained set in the third experimental session. First, we observe a specific improvement for reading pronounceable strings generated from a particular set of letters, a result that must imply a change in the state of the reading system which is confined to a subset of orthographic representations rather than the enhancement of a general procedure that operates on any letter sequence. Second, the data from the letter matching task on nominal identity (Exp. 1b) suggests that the identification of single letters from the trained set does not proceed faster than the identification of letters from the untrained set. Third, the results from the letter priming experiments (Exps. 2a and 2b) argue against an effect of training on the encoding of letters as abstract types (i.e. orthographic code). From points 2 and 3, it thus seems that the letter set effect observed in the last experimental session does not originate from a better identification of the individual letters that constitute the trained set, divorced from their orthographic context. Fourth, it must be recalled that the letter strings on which training was conducted were constructed by random arrangements of legal English trigrams rather than on the same items as those used in Exp. 3. Therefore, the benefits that emerged from the training procedure cannot originate from the modification of lexical–orthographic (in the sense of whole-word) or semantic representations. The kind of correspondence between the features of the letter strings used in training and of those used in the experiments that examined its effects then suggests that a lower level of representation, corresponding to subword components (e.g. bigrams, or trigrams) was affected. Hence, it seems that training on pronounceable strings enhanced the integration of individual letters into subword components, allowing D.M. to synthesize more rapidly the outcome of his letter-by-letter process when the trained letter combinations were presented again in Exps. 3a and 3b. Evidence for such an intermediate level of representation for letter strings, which involves perceptual units of a larger scale than the single letter but of a smaller scale than the entire string, has been reported in neurologically intact observers (Humphreys et al., 1990).

Besides the differences which arose from the training program between

strings made of letters from the trained and untrained sets that were highlighted above, training also had effects which are not specific to letter set. These appear to be additive with the benefits which are restricted to items made of letters in the trained set. Thus, as can be seen in Fig. 9A, average RTs declined markedly as experimental sessions progressed, and this even for items of the "untrained" set. The lack of specificity of this effect suggests that it does not involve a particular set of orthographic representations, but rather that one or several general processes which contribute to the overt identification of letter strings were either developed in D.M. or were rendered much more effective than they were previously. The results of the previous experiments showed an equally increased rate of letter identification for the trained and untrained letter sets. From this, it appears that the nonspecific process which affected performance in Exp. 3a is one involved in the derivation of the identity of the constituent letters of word and nonword strings.

In addition, it should also be noted that, as sessions progressed, the effect of stimulus lexicality on RT's diminished dramatically for items in both the trained and untrained sets (Exp. 3a). This reduction of the lexicality effect from one experimental session to the other suggests that D.M.'s reliance on a lexical process for the overt naming of letter strings, which lead to markedly shorter RTs with words than with nonwords in the baseline session, diminished as training progressed. It should be pointed out however that Exp. 3b showed that an advantage for words over nonwords still occurred in the last experimental session. It therefore seems that training did not entirely abolish D.M.'s reliance on lexical operations for word naming. Because of the large word length effect which is the main feature of D.M.'s reading disorder (see Figs. 2 and 10A), it can be inferred that the initial lexical process seen in the baseline session differed from the holistic visual word recognition which characterizes normal reading. From previous observations in pure alexics (Bub et al., 1989; Bub & Arguin, 1993; Coslett & Saffran, 1989; Reuter-Lorenz & Brunn, 1990; Shallice & Saffran, 1986), it appears possible that holistic word encoding did occur in D.M., but that the activation resulting from this encoding was too weak to allow the explict recognition of the item. Alternatively, it is also possible that the lexicality of the target facilitated the integration of the orthographic components of words into the phonological code upon which naming depends, due to the existence of lexical phonological representations.

Exp. 4: Word length effect. The purpose of Exp. 4 was to determine whether the reduction of reading latency in D.M. was related to a decrease or even an elimination of the letter-by-letter procedure that is characteristic of pure alexia. Figure 10 illustrates the effect of word length on RT's that was observed for words made of letters from the trained and untrained sets in each testing session (Exp. 4a). The slopes of the

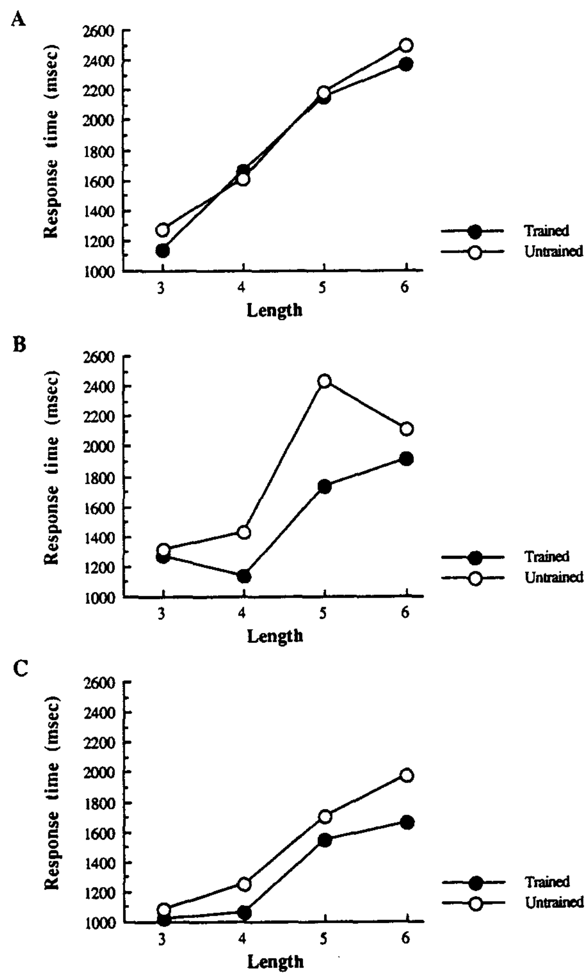

FIG. 10. Average response latencies in the naming of words of varying length (Exp. 4a) on each experimental session where the experiment was conducted.

linear regressions of the effect of stimulus length on response latencies are presented in Table 4. Corresponding error rates are shown in Table 5. The correlation between RT's and error rates was not significant ($r = -.29$; *n.s.*), which indicates no speed-accuracy trade-off.

The main features of the results revealed by the analyses reported below are: (1) A non-specific reduction of RT's for items of the "trained" and "untrained" letter sets as training progressed. (2) An additional reduction of RT's for items made of letters of the trained set on the second and third experimental sessions. On this last session, the advantage for

TABLE 4
Slopes of the Effect of Word Length (in msec/Letter) and Correlation Provided by the Linear Regression in Each Experimental Session where the Effect of Word Length Was Examined (Exp. 4a)

Session	Letter set	Slope	Correlation
Baseline	Trained	420.9	.99
	Untrained	424.2	.99
2nd	Trained	253.2	.88
	Untrained	338.3	.82
3rd	Trained	240.6	.95
	Untrained	312.9	.99

words of the "trained" set was shown to resist case alternation. (3) The effect of word length was significant in all experimental sessions.

The ANOVA applied on RT's included the factors of session (baseline, 2nd, or 3rd), letter set (trained or untrained), and length (3, 4, 5, or 6 letters). Main effects were observed for session [$F(2, 283) = 21.9$; $p < .001$], letter set [$F(1, 283) = 8.3$; $p < .005$], and length [$F(3, 283) = 55.0$; $p < .001$]. Thus, as sessions progressed, a major reduction of average RT's—from 1790 msec in the baseline session to 1563 msec in the second session, and 1407 msec in the third session—occurred. The main effect of letter set indicates shorter RTs for items from the trained set. In addition, the effect of length reveals a regular increase of RTs with increasing number of letters in the string and is congruent with the large slopes of RTs as a function of length shown in Table 4. No interaction was significant. However, planned comparisons of items from the trained and untrained sets at each experimental session indicated a similar performance for the two sets in the baseline session [$F(1, 283) < 1$], but shorter RTs with items made of letters from the trained set in the second [$F(1, 283) = 6.3$; $p < .005$] and third [$F(1, 283) = 4.8$; $p < .01$] sessions. The

TABLE 5
Error Rates (%) Observed in Each Experimental Session where the Effect of Word Length was Examined (Exp. 4a)

		Word length			
Session	Letter set	3	4	5	6
Baseline	Trained	8.3	6.7	14.3	.0
	Untrained	7.7	.0	.0	.0
2nd	Trained	.0	13.3	15.4	9.1
	Untrained	7.7	.0	.0	16.7
3rd	Trained	10.0	5.0	15.0	10.0
	Untrained	10.0	10.0	5.0	.0

analysis of error rates was performed separately for items from the trained and untrained letter sets with a χ^2. No significant effect was seen on error rates for the items made either of letters in the trained [$\chi^2(6)$ = 3.3; *n.s.*] or untrained [$\chi^2(6)$ = 5.4; *n.s.*] sets.

As had been done in the assessment of reading of four-letter strings, the effect of word length was examined with items printed in a case alternated format on the third experimental session (Exp. 4b). The results from this additional task were compared to those obtained in the same session with uppercase items. The average RTs are illustrated in Fig. 11 and error rates are shown in Table 6. The correlation of RTs with error rates was null (r = .00; *n.s.*), thus indicating no speed-accuracy trade-off. The analysis of variance applied on RTs indicated main effects of the letter set from which items were made [$F(1, 269)$ = 20.4; $p < .001$], of the length of the words [$F(3, 269)$ = 53.1; $p < .001$], and of the format in which items were printed [$F(1, 269)$ = 9.0; $p < .005$]. No interaction was significant. The main effect of letter set shows shorter RTs with words from the trained set than with words from the untrained set. Also, RTs increased as the number of letters in the items increased and response latency was shorter with items printed in uppercase than with items in a case alternated format. No significant effect was observed on error rates (trained set: [$\chi^2(6)$ = 3.0; *n.s.*]; untrained set: [$\chi^2(6)$ = 1.6; *n.s.*]).

The experiments conducted to examine the effect of word length on D.M.'s reading times provided results that largely parallel those observed with four-letter items, which were presented in the previous section. Thus, the main finding here is that, on the third test session, words made from letters in the trained set were read faster than words made of letters from the untrained set. In addition, this result was not affected by printing items in a case alternated format, as indicated by the lack of interaction between letter set and visual format in Exp. 4b. As for the results of the previous experiment, it appears that the shorter RTs for words of the

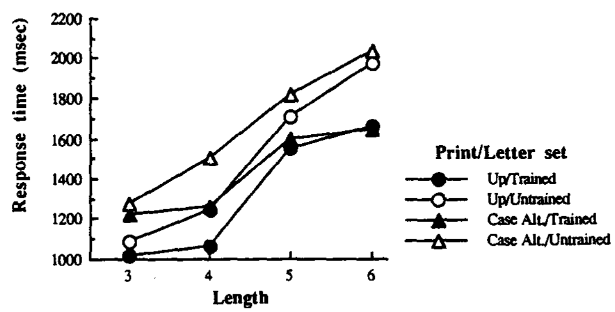

FIG. 11. Average response latencies in the naming of words of varying length printed in uppercase and case alternated formats (Exp. 4b).

TABLE 6
Error Rates (%) Observed in the Word Length Experiment of the Third Experimental Session with Items Printed in Uppercase and Case Alternated Formats (Exp. 4b)

		Word length			
Print	Letter set	3	4	5	6
Uppercase	Trained	10.0	5.0	15.0	10.0
	Untrained	10.0	10.0	5.0	.0
Case alt.	Trained	.0	5.0	31.6	10.0
	Untrained	.0	5.0	15.0	.0

trained sets in Exps. 4a and 4b can be explained in part by an effect of training on representations involved in the assembly of subword letter combinations. The facts upon which this conclusion was reached have been presented in detail in the discussion of Exp. 3.

Contrary to Exp. 3, however, Exp. 4a revealed shorter RTs for words made of letters in the trained set even on the second experimental session, that is after training on isolated letters but before training on letter strings. It therefore seems that the repeated execution of name identity matches of letter pairs led to a facilitation in the subsequent identification of strings made from the letters presented during this training. Because of the difference in the visual format in which items were presented between the training and experimental sessions, it appears that this effect occurred at a level where the identities of written stimuli are represented under a nonvisual code. Since the nominal matching task actually involved the encoding of the identity of single letters, it might be added that the level of representation affected by the letter training must concern representations corresponding to the identities of individual letters in the trained set. Although this appears as the only reasonable explanation for the letter set effect on the second experimental session, there is no clear additional evidence to support it. Thus, besides Exp. 4a, no other experiment showed any performance difference between trained and untrained items on the second experimental session. In particular, in Exps. 1b, 2a, and 2b, where the recognition of isolated letters was tested, one would expect such a difference to occur if the identities of the letters that had been the subject of training were encoded better on this experimental session. Therefore, the available evidence does not provide a straightforward and empirically supported explanation for D.M.'s better performance on words made of letters in the trained set after the training sessions on name identity matches of letter pairs.

In addition to the effect of training that was specific to the letter set on which it was applied, a nonspecific benefit also occurred in that RTs gradually reduced between the baseline to the third experimental sessions even for items made of letters of the untrained set. A comparable nonspecific benefit from training was also apparent in Exps. 1b, 2a, 2b, 3a, and 3b. It has been proposed that this nonspecific effect of training results from an improvement in the process by which D.M. derives the identity of individual letters.

Despite the major improvement in D.M.'s reading latency following the training program, no qualitative change is apparent in the process by which he decodes letter strings. Thus, in all experimental sessions, a marked effect of stimulus length on naming latency was observed (see Table 4). From this, it then appears that the major benefit which originated from the training conducted—averaged over words and nonwords, the benefit is 37% on four-letter strings (Exp. 3a); averaged across words from three to six letters in length, the benefit is of 21% in Exp. 4a—did not eliminate D.M.'s letter-by-letter reading procedure. In addition, the effect of stimulus length was not significantly affected by the training procedures, as shown by the lack of any interaction between the factor of stimulus length and those of session or letter set. Nevertheless, there is a clear trend for such an effect, as can be seen in Table 4. From the baseline to the third experimental session, the slope of RT's as a function of stimulus length was reduced by 43% for items made of letters in the trained set and by 26% for untrained items. It seems that the small number of trials available for each word length—in particular for the baseline and second sessions; see the description of methods—may be responsible for the lack of power of the statistical procedure in showing a significant reduction of the word length effect in D.M.

This trend toward a decreasing word length effect suggests that the training program has reduced the time required by D.M. to process individual letters constituting the trained, and to a lesser degree, the untrained sets. That is, given a letter-by-letter reading procedure, a reduction of the word length effect implies that the time required for the processing of each individual letter is reduced accordingly. From the observations reported above, it appears that this effect of the training program on the impact of word length originates from two separate sources. One appears related to a non-specific reduction in the time required by D.M. to encode the identity of individual letters in his letter-by-letter reading procedure. The results of the previous experiments have indicated that this improved identification performance for individual letters equally affected items from the trained and untrained sets. It then may be suggested that better letter identification contributed to reduce the word length effect for both sets of items. The other source appears related to the benefits of the rehabilitation program which are specific to the trained letter set. It was proposed above that this set-specific benefit reflects an improved assembly of individual letters into subword letter combinations by D.M. Since this faster assembly operation implies a

reduction of the time spent on the processing of each individual letter, it may account for the additional reduction of the word length effect for items made of letters from the trained set.

GENERAL DISCUSSION

Based on the hypothesis that the impairment responsible for the slow and sequential decoding of words in D.M.—and possibly in pure alexia in general—is the failure to encode letter identities as abstract types (i.e. orthographic code), a remediation attempt which tried to reinstate normal letter type encoding was conducted. The training procedures designed to this end involved the matching of pairs of uppercase and lowercase letters of different fonts on the basis of their nominal identity and the overt reading of orthographically legal four-letter strings under time pressure.

As indicated by the various experiments that were conducted to assess the magnitude and nature of benefits of the training procedures on D.M.'s reading, the rehabilitation program effected major improvements of D.M.'s performance in the decoding of written material which were apparent in every experiment that assessed the outcome of the training program. Nevertheless, this benefit was not due to the reinstatement of normal letter type encoding and did not produce a qualitative change in the procedure by which words are identified—i.e. letter-by-letter. The changes appear to involve two components.

One has been qualified as nonspecific, in that it affects items from both the trained and untrained letter sets. This effect seems to correspond to an increased rate of letter identity encoding. Thus, in tasks where identification of the stimuli was required (i.e., all experiments except Exp. 1a), a reduction of RT's was observed between consecutive experimental sessions. In addition, in Exp. 4b, an important—although nonsignificant—reduction of the effect of word length on RT's was apparent for items of the trained set and, to a lesser degree, the untrained set. This is again congruent with an increase in the rate of letter identification as a consequence of the training program. Since this effect occurred even with items that had not been presented during the training sessions, it was proposed that it involved a general procedure transcoding letter shapes into a representation of their identities rather than the state of a particular set of orthographic representations. As discussed previously, in light of the letter priming data (Exp. 2), it appears doubtful that this improved identification of letters proceeded through the letter type pathway. One alternative procedure, yet to be verified, by which D.M. may identify individual letters is in the direct mapping of letter shapes onto phonological representations of letter names.

The other component of the benefits that resulted from the rehabilitation attempt was specific to the stimuli made of letters from the trained set and was observed only in tasks that required the identification of letter strings (Exps. 3 and 4). On the second experimental session, a set-specific effect was observed in Exp. 4a, where RT's were shorter and the impact of word length appeared weaker (see Table 4) for items made of letters from the trained set, even though performance had improved for items of the untrained set also. This set specific benefit may be attributed to the training which occurred on the letter matching task since it preceded the beginning of training on letter strings. It thus seems to result from an improved encoding of the identities of the letters that constituted the trained set. However, as indicated previously, we failed to replicate this set-specific benefit from training in all the other experiments which involved the identification of written stimuli, and therefore it does not appear very reliable.

In contrast, in experimental session three, a clear set-specific benefit was apparent in both Exps. 3 and 4. In these experiments, RT's were shorter with items made of letters from the trained set. Since an unambiguous benefit that is specific to the trained letter set only occurred after string training, it was proposed that this aspect of the training program affected the assembly of individual letter identities into intermediate representations of letter combinations (i.e. bigrams or trigrams). Congruent with the proposal that operations on units of a larger scale than the single letter were affected, results in tasks which required the identification of individual letters (Exps. 1 and 2) did not provide any evidence for a set-specific performance improvement in D.M. Because this particular component of the effect of rehabilitation was restricted to items that had been shown in training, it was proposed that it directly affected the state of orthographic representations involved in the integration of individual letters into letter combinations rather than a general procedure contributing to the assembly process.

In addition to the massive improvements observed in D.M.'s reading performance, another gain achieved by the work presented here is that the observations provide interesting clues with respect to the nature of the fundamental impairment responsible for pure alexia and to the kind of specialized function that is executed by the left occipital lobe, damage to which produces the reading disorder.

Roughly, three rival categories of deficits have been assumed to cause pure alexia. They are: an impairment in the encoding of letter shapes (Rapp & Caramazza, 1991), an impairment of the identification operation for letters (Arguin & Bub, 1992a; Farah & Wallace, 1991; Friedman & Alexander, 1984; Kinsbourne & Warrington, 1962; 1963; Levine & Calvanio, 1978; Reuter-Lorenz & Brunn, 1990), and an impairment in the recognition of words as perceptual units (Kay & Hanley, 1991; Patterson & Kay, 1982; Warrington & Shallice, 1980).

As mentioned in the introduction, low-level perceptual deficits may

occur in patients with pure alexia, and some authors have maintained that, when found, such impairments should be taken as the cause of the reading deficit (Price & Humphreys, 1992; Rapp & Caramazza, 1991). However, other reports have shown that pure alexia may dissociate from a disorder in shape encoding (Arguin & Bub, 1993a; Warrington & Shallice, 1980). The present report adds to the evidence that a low-level perceptual impairment is not required to produce the reading disorder. Indeed, D.M.'s performance in Exp. 1a, which required the physical matching of letter pairs argues against this hypothesis. As shown in Fig. 7a, his RT's in this task were quite short, even in the baseline session. To serve as a basis of comparison, five age matched untrained controls were tested in a comparable task of letter matching on the basis of physical identity. The average RT of the normal control who responded the fastest was of 615 msec, which is 96 msec *longer* than the average RT shown by D.M. in this task in the baseline experimental session. This clearly suggests that D.M.'s encoding of letter shapes is preserved. In addition, and perhaps more importantly, the results of the rehabilitation attempt have shown a dissociation between D.M.'s improvement in the identification of orthographic stimulation and his letter shape encoding. Thus, in experiments where identification of written stimuli was required, marked reductions of response latencies were noted. In contrast, the benefits from training in Exp. 1a, where letter pairs were to be matched on physical identity, were much weaker and seem comparable to what might be expected with practice from a neurologically intact individual. A correlation performed between D.M.'s response latencies in each condition of Exps. 1a and 1b—letter matching on physical and nominal identity, respectively—confirms this dissociation and indicates that any potential improvement of letter shape encoding can only account for 6.1% of the effects observed on his letter identification times. These results emphasize that the main constraint on D.M.'s recognition of written material does not lie in the encoding of visual shapes.

A marked slowness of letter identification has been noted on repeated occasions in patients with pure alexia and a number of authors have suggested that it may be responsible for the incapacity of these individuals to recognize words as perceptual units. The observations reported here suggest that the mere slowness of letter identification is an unlikely basis for a complete account of the disorder. Thus, we have shown a major improvement in D.M. for the identification of isolated letters and of letters within strings. Moreover, in the task of letter matching on nominal identity (Exp. 1b) conducted on the third experimental session, D.M.'s average RT was 52 msec shorter than that of the fastest of five age-matched normal controls who were tested in a comparable experiment. In spite of this, Exp. 4 has shown unambiguously that D.M. still read words using a letter-by-letter procedure at the end of the rehabilitation program. In addition, at that time, his overall reading latencies were much longer than what may be expected from a normal reader. These results thus indicate a dissociation between letter-by-letter reading and a reduced rate of letter identification.

We propose that if a letter identification deficit is responsible for pure alexia, the critical feature by which letter identification in pure alexics differs from that in normals is not quantitative but rather *qualitative*. Thus, besides the characteristic letter-by-letter decoding of words, the other main aspect which remained unchanged by the rehabilitation process in D.M. is the lack of any clear indication of name identity priming (i.e. D/SN) in a task of overt letter identification. It was argued above that this result reflects a difference between D.M. and normal readers in the procedure used to identify letters. More precisely, whereas normals base their explicit identification of letters on the activation of letter type representations, D.M. does not use this representation system. As discussed in a previous section, there exists independent evidence from neurologically intact individuals and a split-brain patient which suggests that the failure to encode letters as abstract types may have a causal relationship with letter-by-letter reading.

A third category of explanation for pure alexia is that it results from an incapacity to process words as perceptual units, either because of damage to the orthographic lexical representation system (Warrington & Shallice, 1980)—also referred to as a "word-form deficit"—or because of a disconnection between peripheral letter analyzers and the word-form system (Kay & Hanley, 1991; Patterson & Kay, 1982). In a way, the account proposed here may be considered as a further adjunct to these views since we suggest that this incapacity for whole-word reading is a fundamental feature of pure alexia. Our account departs from the word-form hypothesis or the disconnection interpretation however, since it assumes that an encoding impairment of letters and words as abstract orthographic entities lies at the origin of the reading deficit.

Conclusion

We reported an attempt at the remediation of pure alexia. The training procedures used failed to fundamentally affect the nature of the processing impairment for written material. They nevertheless resulted in a massive improvement of the reading performance of the patient on which they were applied. The observations gathered in the course of our rehabilitation attempt have contributed several elements of information with respect to the nature of the limiting factor which affects the processing of written stimuli in pure alexia. In particular, it appears that the incapacity to encode letters as abstract types is a critical constraint and that it may be responsible for the slow and sequential decoding of individual letters that characterizes word recognition in this disorder.

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