ELSEVIER

Cognition 82 (2001) 77–126

COGNITION

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Deep dyslexia in the two languages of an Arabic/ French bilingual patient

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Received 29 December 2000; accepted 11 June 2001

Abstract

We present a single case study of an Arabic/French bilingual patient, ZT, who, at the age of 32, suffered a cerebral vascular accident that resulted in a massive infarct in the left perisylvian region. ZT's reading displays the characteristics of the deep dyslexia syndrome in both languages, that is, production of semantic, visual, and morphological errors, and concreteness effect in reading aloud and impossibility of reading nonwords. In the first part of this paper, using a three-route model of reading, we account for the patient's performance by positing functional lesions, which affect the non-lexical, the semantic lexical and the non-semantic lexical routes of reading. Phonological priming observed in a cross-language visual lexical decision task indicates that implicit assembled phonological recoding is possible. The above lesions and implicit nonword reading characterize the output form of deep dyslexia. However, error distribution reveals dissociations across languages (e.g. the semantic error rate is higher in French whereas translations are more frequent in the Arabic testing) that cannot be accounted for within a three-route model. In the second part, extensions to Plaut and Shallice's connectionist model (*Cognitive Neuropsychology*, *10* (5) (1993) 377) are proposed to account for the translinguistic errors observed. ZT's error distribution is compared to that obtained by Plaut and Shallice after lesions had been applied at different locations through the 40–60 network. The overall syndrome of deep dyslexia found in both languages is explained as resulting from lesions along the direct (O → I) and output (S → Ip, Ip → P) pathways of reading. Lesions along the output pathway mostly affecting S → Ip connections in French and Ip → P connections in Arabic account for discrepancies in ZT's error pattern across tasks and languages. This case study demonstrates the superiority of a connectionist approach for

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PII: S0010-0277(01)00148-2

predicting the error pattern in deep dyslexia.

Keywords: Deep dyslexia; Bilingualism; Arabic; French; Connectionism

1. Introduction

Early accounts of deep dyslexia (Marshall & Newcombe, 1973) describe it as a symptom-complex characterized by semantic errors in reading, together with the co-occurrence of derivational and visual errors, substitutions of function words, and difficulty in or even impossibility of reading nonwords. Coltheart (1980a) extends to the initial list a set of other co-occurring symptoms, i.e. lexical derivation of phonology from print impaired, abstract words harder to read aloud than concrete words, writing spontaneously or to dictation impaired, auditory-verbal memory impaired, reading of a word dependent on its context, verbs harder to read than adjectives which are harder than nouns, function words harder to read than content words. The list is then reviewed and edited in Coltheart, Patterson, and Marshall (1987) who take out from the list the three last features, thus limiting to eight the number of symptoms claimed to co-occur mandatorily with semantic errors in deep dyslexia.

Initial attempts to account for the deep dyslexia syndrome were proposed within cognitive neuropsychological models. The multiple-impairment hypothesis postulates that several deficits along the lexical route (semantic and non-semantic routes for reading) and the non-lexical route are responsible for the co-occurrence of the types of errors observed in the deep dyslexic patient's reading performance. More specifically, within the three-route model (Coltheart et al., 1987; Morton & Patterson, 1980; Shallice & Warrington, 1980), semantic and morphological errors in reading aloud, difficulty in reading abstract words and inability to read nonwords aloud are claimed to arise through impairments at four independent lesion sites within the language-processing system: (1) lesion to the assembled pathway that allows the identification of sub-word orthographic segments and their conversion into phonological segments, then into the oral production of a letter string; (2) damage to the addressed pathway which allows reading aloud of words with mediation of the semantic system; (3) impairment of the addressed pathway which allows reading of words without mediation of the semantic system; and (4) damage to the semantics of abstract words.

In subsequent research, however, criticisms have been raised leading to a weakening of the "syndrome-complex" theory. More specifically, even though semantic errors have been found to represent the central symptom of deep dyslexia as claimed initially, the close association and mandatory co-occurrence of the other symptoms have been questioned. For example, Allport and Funnell (1981) reported an absence of part-of-speech effect; Caramazza and Hillis (1990) suggested that some of the symptoms described do not necessarily appear together with semantic errors.

Another functional interpretation of deep dyslexia has been offered by Coltheart

(1980a,b, 1983, 2000) and Saffran, Bogyo, Schwartz, and Marin (1980) who claim that in deep dyslexia, a very large lesion in the left hemisphere destroys the patient's reading ability, hence leading to reading by an intact but weak language system located in the right hemisphere rather than reading via an impaired language system located in the left hemisphere. This hypothesis has been empirically based on similarities in reading performance of deep dyslexic patients and of patients assumed to be reading with the right hemisphere. Right hemisphere reading has been observed as having limitations, which include incapacity in reading abstract words and function words, in distinguishing among semantically related words, and in converting an orthographic code into a phonological code. Such limitations should explain the deep dyslexic's difficulty in reading abstract and function words, nonwords and bound morphemes. However, this hypothesis has been frequently questioned on several grounds. Normal subjects tested in reading tasks involving the left visual field (LVF) presentation do not behave like deep dyslexic patients (e.g. Patterson & Besner, 1984). When compared to split-brain patients, deep dyslexic patients have shown better reading in LVF presentation (Michel, Hénaff, & Intriligator, 1996; Patterson & Besner, 1984). In addition, Roeltgen (1987) reported the case of a patient who lost symptoms of deep dyslexia following a second left hemisphere lesion. Glosser and Friedman (1990) examined deep dyslexia cases with relatively small size lesions, hence refuting the claim that the large size of the lesion in the left hemisphere in deep dyslexic patients automatically induces right hemisphere compensation. More recently, a study by Price et al. (1998) in which neuroimaging techniques were used has provided no support for an exclusive reliance on right hemisphere reading by deep dyslexics (but see Coltheart, 2000 for conflicting views).

Connectionist approaches to deep dyslexia have also been attempted. Hinton and Shallice (1991) and then Plaut and Shallice (1993) have succeeded in reproducing the co-occurring errors found in deep dyslexia by lesioning a connectionist network at different sites. More specifically, the model designed by Plaut and Shallice (1993) is capable of simulating most of the simultaneous characteristics of the syndrome by lesioning various connections in a network trained to map orthography onto semantics and semantics onto phonology. The authors showed that lesions made at different sites produce the co-occurrence of visual, semantic and phonological errors as well as most of the lexical effects observed in deep dyslexia. In their model, the co-occurrence of these different error types derives from the nature of the computation that the whole system carries out. In contrast with the multiple functional impairment approach, in the Plaut and Shallice (1993) connectionist model, lesions in different parts of the network may result in the same overall syndrome. At the same time, other aspects of the syndrome may differ between lesion sites. As an example, Plaut and Shallice (1993, p. 487) showed that a lesion simulated on the direct pathway produced visual and semantic errors together with a concreteness effect. Lesions to the clean-up network produced the same error pattern without the concreteness effect.

Although the deep dyslexia syndrome has incited considerable research and resulted in numerous publications, very little has been reported on bilingual deep dyslexic patients. Most of the studies have dealt with errors either in monolingual patients or in one of the languages of the patients described. In this paper, we report the first case of an Arabic/French bilingual patient who, in addition to showing all of the symptoms of output deep dyslexia in his two languages, produces translations into French, his second language. Wydell and Butterworth (1999) report the case of a 16-year-old English/Japanese bilingual boy who showed the symptoms of developmental dyslexia in English only. Byng, Coltheart, Masterson, Prior, and Riddoch (1984) present the case of a deep dyslexic patient whose first language was Nepalese but who could also read in English. The patient showed most of the features of the deep dyslexia syndrome in English but reading was almost impossible in Nepalese. Most of the patient's oral productions were translations into English. The existing theoretical approaches to deep dyslexia such as the multiple-impairment interpretations, the right hemisphere hypothesis or the connectionist models, have not provided any account for such types of errors either because they have been addressing monolingual patients or because of an implicit understanding that the interpretations offered for monolingual patients would equally apply to patients speaking two or more languages. Furthermore, such approaches have not made any provision for languages with different types of alphabets.

In the case we are presenting, the patient's two languages are highly contrastive. Arabic and French display two different alphabets (Latin vs. Arabic) and two different writing modes (right-to-left vs. left-to-right). In addition, French is characterized by a deep or opaque orthography, i.e. orthography with an irregular spelling in that sound and spelling do not always correspond in the language. Arabic, on the other hand, exhibits two types of orthography: (1) an orthography "with diacritics", i.e. in which consonants and long vowels are represented by letters whereas short vowels are represented by symbols; and (2) an orthography "without diacritics", i.e. where only consonants and long vowels are represented, short vowels being absent. The two types of orthography have been referred to in the literature on Semitic languages as shallow and deep, respectively (Bentin & Ibrahim, 1996). However, it is important to point out that Arabic orthography, whether deep or shallow, is highly regular in that there is a one-to-one correspondence between letters, diacritics, and phonemes. A detailed description of the Arabic orthographic system is presented in Section 2.

It has been suggested in the literature on reading languages with deep and shallow orthographies (Bentin & Ibrahim, 1996) that the relative involvement of the phonological and the lexical routes in reading depends on the degree of regularity or transparency in the spelling-to-sound correspondence. According to this claim, readers in languages with deep orthography such as English or French would rely more on the lexical route whereas readers in languages with shallow orthographies such as Spanish or Portuguese would be using non-lexical mechanisms (Bentin & Frost, 1987; Katz & Feldman, 1983). Readers of languages with both types of orthography such as Arabic or Hebrew are, therefore, expected to use either route depending on the type of orthography presented. According to the orthographic depth hypothesis (Katz & Frost, 1992; Wydell & Butterworth, 1999), the lexical route (addressed routine) predominates in alphabetical languages with deep orthography whereas the non-lexical route (assembled routine) predominates in languages with shallow orthography. In Hebrew, for instance, experiments by Frost (1994) in naming and lexical decision tasks (LDTs) conducted with normal subjects showed that subjects behave differently in naming tasks depending on whether stimuli are written in deep or shallow print. Larger frequency effects and semantic priming effects are observed when the subjects are presented with deep orthography. Therefore, one may expect deep dyslexic patients to produce more semantic errors when reading stimuli presented in deep orthography.

To our knowledge, only two cases of acquired reading disorders have been published on languages with two types of orthography. A first study was conducted by El Alaoui-Faris et al. (1994) who reported the case of an Arabic-speaking patient suffering from alexia without agraphia. The patient showed no difference whether tested in shallow or deep orthography. However, given that the patient recovered from her reading impairment despite the presence of left cerebral lesions, the authors concluded to a bi-hemispheric participation in reading. Their interpretation was based on studies of pure alexic patients (Coslett & Saffran, 1989) and on studies in reading acquisition (Seymour & Elder, 1986), both suggesting a participation of the right hemisphere in reading. According to El Alaoui-Faris et al., the participation of the right hemisphere is maintained in adult Arabic readers because of the level of complexity of the visuo-spatial activity involved in reading deep orthography of Arabic. The second case was reported by Birnboim and Share (1995) who presented a Hebrew-speaking surface dyslexic producing more reading errors in the deep than in the shallow orthography, but this effect did not reach significance.

Studies on deep dyslexic patients speaking languages with shallow orthography have presented opposing results. Ardila (1991) examined 41 Spanish-speaking aphasic patients who did not produce semantic errors. He concluded that deep dyslexia never develops in speakers of languages with shallow orthography. This claim was, however, refuted by the subsequent report of three deep dyslexic Spanish-speaking patients (JMK in Ferreres & Miravalles, 1995; ON and MG in Ruiz, Ansaldo, & Lecours, 1994), of one deep dyslexic Portuguese-speaking patient (MAC in Delgado, 1998) and of one phonological dyslexic Spanish-speaking patient (AD in Cuetos, Valle-Arroyo, & Suárez, 1996).

With respect to languages with deep orthography, extensive research has been undertaken on English-speaking deep dyslexic patients, resulting in a distinction between the input, the central and the output forms, depending on the lesion site, or the route responsible for the production of semantic errors. In the input and central forms, semantic errors arise from an impairment affecting respectively access to the semantic system, and the semantic system itself. In the output form, semantic errors arise from impairment in accessing phonology from semantics. Four cases of output deep dyslexic English-speaking patients have been documented (JA in Katz & Lanzonni, 1992; GR in Hildebrandt & Sokol, 1993; JC in Buchanan, Hildebrandt, & MacKinnon, 1994; and LW in Newton & Barry, 1997). In three of these cases, the authors aimed at demonstrating that implicit access to the sub-lexical phonology of words (JA and GR) and nonwords (JC) is preserved in output deep dyslexia.

Surprisingly, very few cases of acquired reading disorders have been reported in French-speaking patients. One case of phonological dyslexia was examined by

Derouesné and Beauvois (1985). In a case of deep dyslexia reported by Lecours, Lupien, and Bub (1990) analysis was limited to the morphological errors produced by the patient. Finally, the literature contains two cases of deep dysphasia: Cardebat, Puel, Démonet, and Nespoulous (1991), whose patient presented a mild deficit in auditory lexical decision in the absence of a central semantic impairment as well as a severe impairment of verbal short-term memory (STM); and Valdois, Carbonnel, David, Rousset, and Pellat (1995) who presented an exhaustive case study of a French-speaking patient with surface dyslexia, deep dysphasia and deep dysgraphia. In repetition, their patient produced the same types of errors as found among deep dyslexics in reading aloud.

To summarize, cases of deep dyslexia have been reported in languages with both deep and shallow orthography as well as in languages with the two types of orthography. However, with respect to languages with shallow orthography and those with the two types of orthography, the existing evidence is still largely insufficient and does not provide a clear picture of whether and how the type of orthography may influence deep dyslexia. Furthermore, the very few studies reporting on acquired or developmental dyslexic bilingual subjects reveal conflicting results. In the two cases reported, one notices that only one of the two languages is affected, and that the language affected may be either the first or the second language.

The present study is divided into two parts. First, we localize the functional lesions responsible for the reading impairments of the Arabic/French bilingual patient by resorting to a three-route model of reading. In the second part, we propose accommodations to the Plaut and Shallice (1993) connectionist model in order to account for the characteristics of bilingual deep dyslexic patients. Then, we compare the multi-impairment hypothesis and the connectionist approach with regards to their ability to account for the deep dyslexia syndrome.

Before proceeding into a detailed investigation of this case, we first propose a concise description of the most relevant linguistic features of Arabic and French. We also emphasize the linguistic properties that are common to the two languages spoken by the patient as well as their contrastive aspects.

2. Linguistic features of Arabic and French

2.1. The alphabets and the writing systems

Arabic and French have an Arabic and a Latin alphabetical system, respectively, written on a horizontal axis. However, whereas French is written from left to right, Arabic is written from right to left in a connected fashion. Furthermore, in contrast to French writing, Arabic does not contrast upper- vs. lower-case or cursive vs. script written forms. With respect to their phonemic inventories, the two languages share 14 consonants and three vowels.

One major feature of Arabic writing lies in the various context-determined graphemic representations taken by each of the 28 letters making the Arabic alphabet. More specifically, each letter may have from two to four distinct allographs

Table 1
Examples of Arabic orthographic representation with and without vowel diacritics

With vowel diacritics	Without vowel diacritics		
كَتَبَ	كتب	kataba	'he wrote'
كُتِبَ	كتب	kutiba	'it was written'
كُتُبٌ	كتب	kutubun	'books'

depending on its graphemic position in word-initial, -medial, -final, or in isolation (e.g. the letter س in سليم, نسمة, لبس, and س, respectively).

Arabic writing involves the use of a set of symbols called diacritics that appear on top or below letters to represent short vowels, gemination, case, and silence.[1] However, diacritic symbols do not normally appear in written Arabic. They are found in the Holy Koran, in children's books, and in pedagogical materials used in the first years of the reading and writing process. They progressively disappear from written texts as the child starts mastering reading and writing. Thus, the Arabic word is restricted to its consonants and long vowels. The absence of short vowel information in Arabic usually results in the presence of homographs in the language that are semantically and phonologically ambiguous. As shown in the examples presented in Table 1, Arabic words without diacritic symbols may carry several meanings and pronunciations, thus requiring the adult reader to rely on the context in which these words appear. This is why diacritic symbols are provided in cases where word ambiguity may distort understanding.

2.2. The morphological systems

In French the prototypical process of word formation is linear affixation, i.e. words are made up of sequences of morpheme segments that are concatenated together in a linear order as shown in the word *trans-form-at-ion*.

In contrast to French, a Semitic language like Arabic exhibits nonconcatenative morphological processes. Simple words are commonly formed on the basis of a discontinuous root of three or four consonants (e.g. /k-t-b/) between which sets of vowels are inserted (e.g. كتب [katab] 'he wrote'; كتاب [kitaab] 'a book'; كتب [kutub] 'books', etc.). In addition to this infixation process, suffixation and prefixation are also typical morphological operations (e.g. [maktab] 'office'; [maktaba] 'library'; [maktabat] 'libraries'). Within recent linguistic accounts such as autosegmental approaches (McCarthy, 1981, 1982), the word كتب [katab] 'he wrote', for instance, consists of three different morphemes: a discontinuous consonantal root /k-t-b/ which specifies the semantic field of the family of related lexical items ('the act of writing' in the above example), a discontinuous set of vowels /i-aa-/ which

[1] Silence or sukuun, which takes a small circle as a diacritic mark, indicates the absence of a vowel either in a CC sequence or in a word-final position.

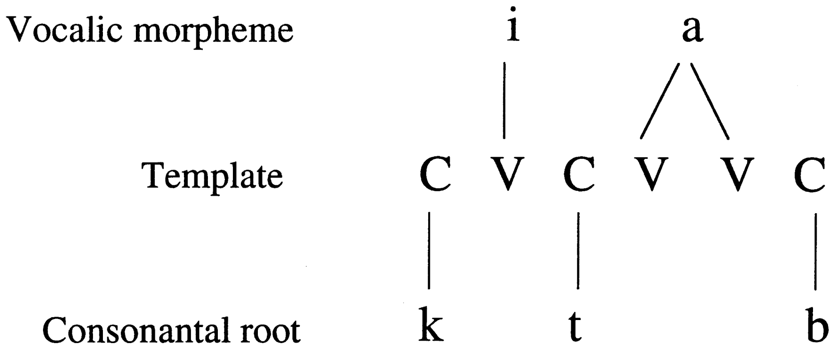

Fig. 1. Internal representation of the word [kitaab] 'book' in Arabic.

identifies the lexical entry and specifies its functional/grammatical categories (the perfective in our example) and a prosodic template CVCVC which allows for distinction between morphological patterns (e.g. for verbs, pattern 1 CVCVC [katab] 'wrote', pattern 3 CVVCVC [kaatab] 'corresponded', etc.). As illustrated in Fig. 1, within this autosegmental approach, word formation involves the mapping of units of the consonantal root and the vocalic morpheme with the template.

Within morpheme-based linguistic models of the Arabic lexicon, lexical items are morphologically related when they share a consonantal root carrying the same meaning (e.g. the consonantal root /b-r-d/ carries the meaning of 'cold' in [barada] 'to cool' and [buruuda] 'the cold'). Words sharing the same consonantal root but whose meanings are different (e.g. /b-r-d/ in [bariid] 'mail' vs. [buruuda] 'the cold') are claimed to appear in separate lexical entries and, hence, are not morphologically related (see Prunet, Béland, & Idrissi, 2000 for details of various views on the Arabic lexicon).

3. Case history

ZT was born in 1962. A right-handed male, ZT is a native speaker of Lebanese Arabic. He started studying Arabic and French at school at the age of 4 in Lebanon. In the school and university he attended, the scientific subjects were taught in French whereas all other subjects were taught in Arabic. After he graduated, he moved to Montreal, Canada in 1984. He then earned a Master's degree in a French-speaking university and worked as an engineer from 1985 to 1993 in two different companies where French was used as a main language. ZT spoke Arabic at home and with friends. Even though ZT demonstrates fluency in his two languages, he considers Arabic as his dominant language. Therefore, in the present study, we will refer to ZT's two languages as L1 and L2 for Arabic and French, respectively.

3.1. Neurological assessment

At the age of 32, ZT suffered a cerebral vascular accident, which resulted in a severe mixed aphasia, a right hemiplegia, a severe bucco-facial apraxia, a transient right facial palsy and a transient homonymous lateral hemianopsia. Diagnosis revealed thrombosis of the left middle cerebral artery. CT scan performed a few days after his admission to the hospital showed an infarction of the left peri-sylvian region. Another scan performed a year later revealed an evolution toward chronicity of the massive infarct in the left peri-sylvian territory (see Fig. 2A). The fronto-temporo-parietal hypodensity also included the insula cortex, the corresponding corona radiata and the left temporal pole (see Fig. 2B).

3.2. Neuropsychological assessment

Neuropsychological testing conducted three weeks post-onset revealed no impairment in construction praxis nor memory problems in complex visual recall tasks. Short- and long-term memory as well as judgment and reasoning capacities were well preserved. On a psychological level, the patient, even though eager to understand his illness, showed signs of frustration, anger, and sadness when unable to communicate.

At a subsequent neuropsychological evaluation performed 6 months post-onset, ZT started using the written mode to communicate. He had become more aware of his severe language disturbances and seemed to have accepted the fact that he would not be able to return to his engineering job.

On the Mesulam test, ZT's score was perfect, thus showing no attention disturbances. The results on the Raven matrices showed an IQ well above normal (110). On the complex figure of Rey, the patient's performance reflected difficulties in the production of details.

With respect to verbal memory, ZT showed well-preserved capacities in learning and in delayed recall of pairs of words from the Wechsler battery, but a poor performance on non-semantically related pairs. The patient's verbal STM was evaluated in French. His performance was then compared to that of three bilingual (Arabic/French) controls matched for age, sex and education. Verbal STM capacity was assessed using span tasks. Different types of stimuli were used: digits, monosyllabic words, letters and nonwords. For each stimulus type, lists of two to eight items were created. Lists of increasing length were presented in both visual and auditory modalities for immediate oral recall. The patient's span was defined as the longest item list recalled in correct order in at least half of the four trials. Results indicated a reduced verbal span in both modalities. In the auditory modality, ZT could recall only three digits (range for controls = 5–8), two words (range for controls = 4–5), two letters (range for controls = 5–6), and two nonwords (range for controls = 3–4). In the visual modality, the patient recalled three digits (range for controls = 6–8), three words (all controls recalled four words), and three letters (range for controls = 4–6). To summarize, in French ZT showed a limited verbal STM in both visual and auditory modalities.

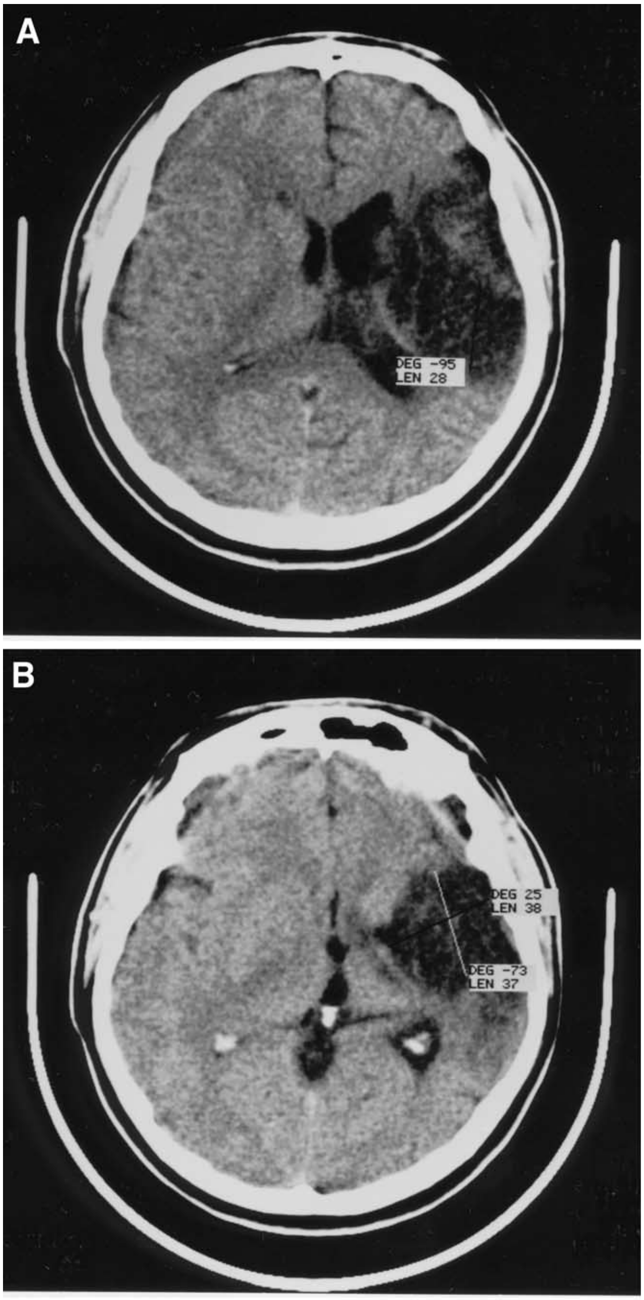

Fig. 2. (A,B) CT scan performed a year post-onset.

3.3. Language assessment

Early language evaluation reported severe mixed aphasia. One year post-onset, language assessment in Arabic and French showed mildly impaired oral comprehension. Oral production was found to be severely impaired with the exception of repetition of simple words in which the patient produced very few errors. Writing to dictation for single letters, words, and nonwords was severely impaired both in Arabic and French. Testing in reading aloud showed a large proportion of semantic errors in both languages, a central feature of the deep dyslexia syndrome. A comprehensive study was then undertaken to investigate whether the patient would produce the other symptoms characterizing deep dyslexia, and whether these symptoms would be present in both languages mastered premorbidly by the patient.

4. Methodology

Native speakers of the two languages tested the patient. Evaluation was conducted in parallel in the two languages, with only one language used in each testing session. To ensure that ZT was assessed in the two languages at the same period of his evolution, tasks in the two languages were administered in alternation. In Arabic, we tried – in as much as the language permits – to control for dialect varieties and hence, to select stimuli that show uniformity across Standard Arabic and Lebanese, the patient's dialect. When relevant, ZT was tested in both Arabic orthographies, shallow and deep. In such experimental settings, two versions of the same set of stimuli were designed, one with vowel diacritics (**w**) and one without (**wo**), which were administered to the patient in alternation and at different times throughout testing.

5. Localization of ZT's functional lesions within a three-route model

We took as a basis for our investigation the functional three-route model for word recognition proposed by Buchanan and Besner (1993). We then brought to this model the two following modifications. First, we combined the input and output phonological lexicons into a single phonological lexicon. A single phonological lexicon presupposes that phonological representations are neither acoustic nor articulatory, but rather abstract representations (see Allport, 1984; Béland & Paradis, 1997). Second, we added route J for the repetition of nonwords. The revised version of this model is illustrated in Fig. 3.

As in Buchanan and Besner (1993), capital letters have been used to identify the different pathways between the different subcomponents of the model. This model comprises three routes for reading: (1) a semantic lexical route B-E-F-D; (2) a non-semantic direct lexical route B-C-D; and (3) a non-lexical route A. It also comprises three routes for repetition: (1) a lexical semantic route I-H-F-D; (2) a non-semantic direct lexical route I-D; and (3) a non-lexical route J.

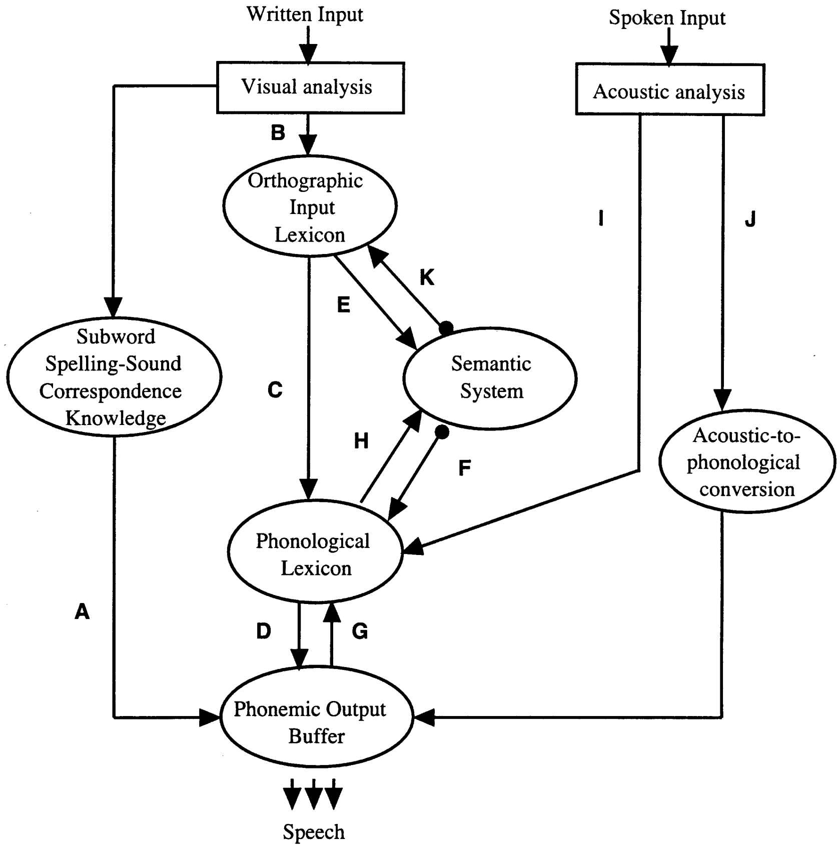

Fig. 3. Functional three-route model for word recognition adapted from Buchanan and Besner (1993).

5.1. Input processing

In deep dyslexia, visual and acoustic analyses (see Fig. 3) are assumed to be intact. It is crucial, however, to assess their integrity before conducting any further investigation.

5.1.1. Visual discrimination

The Arabic stimuli set comprised 80 identical and 80 different pairs of mono- and bi-syllabic words and nonwords. Diacritic symbols were not presented in this task. The patient was instructed to respond orally *yes* when the stimuli of a pair were identical and *no* when they were not. When non-identical, members of a pair differed by one consonant located either in the initial, medial or final position. The non-identical pairs were divided into four subsets: (1) 20 pairs involving graphemically close but phonologically distant consonants; (2) 20 pairs involving graphemically distant but phonologically close consonants; (3) 20 pairs involving graphemically and phonologically close consonants; and (4) 20 pairs involving graphemically and phonologically distant consonants. The four subsets were created in order to control for the potential influence of phonological similarity in the patient's performance. If phonological similarity had any influence on the patient's judgment, a lower score in subsets (2) and (3) than in subsets (1) and (4) is to be expected. ZT's performance on this test was almost flawless (158/160).

The discrimination test in French comprised 160 pairs (80 identical and 80 different) of monosyllabic CV and V words and nonwords presented in lower-case letters. When non-identical, the members of a pair differed by one consonant located either in the initial or final position. As in the Arabic testing, the 80 different pairs were divided into four subsets. ZT obtained a score of 159/160. The results show that ZT's ability in written discrimination is almost flawless in both Arabic and French, an indication that the visual analysis component is unimpaired.

5.1.2. Auditory discrimination

The stimuli were presented auditorily to the patient who was instructed to answer *yes* when the two members of a pair were identical and *no* when they were not.

In Arabic, the stimuli set consisted of 90 pairs (45 identical and 45 non-identical) of monosyllabic words and nonwords. When non-identical, members of a pair differed by only one phoneme in the word-initial or word-medial position. The phonological differences between the two phonemes involved one of the following feature contrasts for consonants: voiced, nasal, and pharyngeal, and one of the feature contrasts for vowels: long, high, and round. ZT's score on this test was almost perfect (88/90).

The French stimuli set comprised 36 pairs (18 identical and 18 non-identical) of mono- and bi-syllabic words differing by one consonantal phoneme in either the word-initial or word-final position. ZT's performance on this test was close to perfect (35/36).

5.2. Access to the orthographic input lexicon

One of the characteristics of deep dyslexic patients is that their performance is surprisingly good in a LDT given the degree of their word reading impairment (Coltheart, 1980a; Patterson, 1979). Therefore, a visual LDT was designed and administered to the patient to test his abilities to distinguish words from nonwords via visual input.

Version **w** presented stimuli written with vowel diacritics, whereas in version **wo** the stimuli were without. Stimuli were printed and randomly administered to the patient without time constraints. He was instructed to respond orally *yes* if he recognized the stimulus as a word and *no* if he did not. In the Arabic version **w**, the stimuli set was made up of 80 mono-, bi- and tri-syllabic words ($n = 40$) and nonwords ($n = 40$). Nonwords were of two types: (1) nonwords created by changing one to two phonemes in real words of the language; (2) nonwords that were not created from words but which respected both the orthographic and phonological constraints of the Arabic language without containing a real consonantal root.

ZT scored 69/80 (86%) producing nine errors on nonwords and two on words. The performance of three Lebanese control subjects who were Arabic/French bilinguals and who were matched for age, educational level and level of bilingualism was 79/80 (99%), 75/80 (94%), and 78/80 (98%) for each of the subjects.

In version **wo**, the stimuli set was the same as in version **w**. ZT's score was 71/80 (89%). The control subjects scored 79/80 (99%), 78/80 (98%), and 76/80 (95%).

In French, the stimuli consisted of 80 mono-, bi- and tri-syllabic words ($n = 40$) and nonwords ($n = 40$). The nonwords were created by replacing one consonant of a word by one consonant whose sound correspondence is phonologically close. ZT obtained a score of 63/80 (79%). Three Arabic/French bilingual control subjects matched for age and educational level scored 72/80 (90%), 73/80 (91%), and 71/80 (89%).

A difference in the performance was observed between Arabic and French in ZT as well as in the controls, most probably reflecting the predominance of Arabic over French in all the subjects. However, ZT's performance was lower than that of the control subjects in both Arabic and French, an indication that access to the orthographic input lexicon is partially impaired.

5.3. Access to the phonological lexicon

An auditory LDT was designed for each language. In Arabic, the stimuli set consisted of 48 mono-, bi- and tri-syllabic words and 48 nonwords. Nonwords were created by replacing one consonant of a word by a phonologically close consonant which shared all feature values but one. The feature contrasts involved were voiced, nasal, emphatic, anterior, continuant, and guttural. ZT's score was 83/96 (86%). The control subjects scored 86/96 (90%), 82/96 (85%), and 75/96 (78%).

In French, the stimuli set was the same as the one used in the visual modality. ZT scored 65/80 (81%). The control subjects scored 63/80 (79%), 70/80 (88%), and 70/80 (88%).

5.4. Reading aloud

Several sets of stimuli (letters, syllables, words and nonwords) were designed in Arabic and French to test the patient's performance in reading aloud. Furthermore, when appropriate, Arabic tests included two lists of stimuli, one with vowel diacritics and one without.

5.4.1. Reading aloud of the alphabet

The patient was requested to read aloud the printed 28 letters of the Arabic alphabet that were presented to him in a randomized fashion. ZT produced 15 errors; four consisted of words beginning with the target letter (e.g. ق → قرد [qird] 'monkey'), two contained the target letter (e.g. ح → صحراء 'Sahara'), six were substitutions (e.g. ت → أ), two were attempts to produce the target letter (e.g. م → [em]), and one remained without response.

With respect to the 26 letters of the French alphabet which were presented to him in a random order and printed in upper case, ZT produced ten errors, eight of which consisted of words beginning with the target letter (e.g. G → [gã] *gant* 'glove';

N → *nous* [nu] 'we'), or containing the target letter (e.g. X → [taksi] *taxi* 'cab'). The two other errors were attempts to produce the letter sound (C → [k, s]), and a semantic association (W → [lɔkɔmɔtiv] *locomotive* 'locomotive' possibly because the letter W is close to the logo of a train transportation company, or because it starts the word *wagon* 'wagon').

5.4.2. Reading aloud of syllables

In Arabic, it was difficult to construct a large set of syllables that would not correspond either to a real word or to a letter name of the alphabet. Therefore, syllable reading aloud was tested only in French.

The French stimuli set was made up of 69 monosyllabic CV and V words and nonwords printed in upper case (e.g. QUE, KA, VU, LO). The patient obtained a score of 34/69 (49%). Many of these errors were comparable to the ones produced in reading aloud of single letters, i.e. ZT's erroneous responses corresponded to French words beginning with the target initial letter sequence (e.g. CU → [kɥizin] *cuisine* 'kitchen'). Other errors consisted in incorrect grapheme-to-phoneme conversion (e.g. AU [o] was read [u]).

5.4.3. Reading aloud of concrete and abstract words

In Arabic, the stimuli set was made up of a total of 108 words; 54 were concrete and 54 were abstract. The stimuli were presented without vowel diacritics. The list is an adaptation of the one used in French (see below) since there exist no reliable frequency table and no reference for the degree of concreteness of words in Arabic. As indicated in Table 2, ZT's error rate is higher on abstract (42/54 = 78%) than on concrete (31/54 = 57%) words. The difference was significant (χ^2 with continuity correction = 4.22, $P < 0.05$).[2]

The French stimuli set was taken from Gagnon (1988) and Valdois et al. (1995). It consisted of 60 abstract and 60 concrete words matched for lexical frequency and length in the number of letters and phonemes. The 120-word list was presented to 34 undergraduate students who were requested to rate the words for concreteness on a 1 to 5 scale. The mean rating was 2.25 (SD 0.46) for abstract and 4.79 (SD 0.28) for concrete words; the difference between two word types was significant ($t(118) = -36.47$, $P < 0.01$). The patient produced more errors on abstract (44/60 = 73%) than on concrete words (26/60 = 43%). The difference was significant ($\chi^2 = 9.90$, $P < 0.01$).

5.4.4. Reading aloud of function words

The Arabic stimuli set comprised 35 open-class items (nouns) and 35 closed-class items (conjunctions, prepositions and pronouns) presented without diacritics. The patient produced 19 errors (54%) on open-class items and 33 errors (94%) on closed-class items (see Table 2). The difference in the proportion of errors was significant ($\chi^2 = 12.63$, $P < 0.001$).

[2] All χ^2 values are reported with continuity correction.

Table 2
Number and percentage of errors for different word categories in Arabic (**w** and **wo**) and French in reading aloud

	Arabic		French	
	No.	% errors	No.	% errors
Concreteness effect				
Concrete (**wo**)	31/54	57	26/60	43
Abstract (**wo**)	42/54	78	44/60	73
Function word effect				
Open class items (**wo**)	19/35	54	18/30	60
Closed class items (**wo**)	33/35	94	30/30	100
Grammatical class effect				
Nouns (**wo**)	117/166	70	23/40	57
Verbs (**wo**)	60/64	94	30/40	75
Adjectives (**wo**)	36/56	64	23/40	57
Nouns (**w**)	109/158	69		
Verbs (**w**)	60/64	94		
Adjectives (**w**)	35/56	62		

The French stimuli set was taken from Gardye, Béland, and Nespoulous (1990). It comprised 30 open-class and 30 closed-class items matched for lexical frequency and length in number of phonemes and letters. ZT produced an error rate of 60% (18/30) on open-class items and of 100% (30/30) on closed-class items. The difference in the proportion of errors was significant ($\chi^2 = 12.60$, $P < 0.001$).

5.4.5. *Reading aloud of nouns, verbs, and adjectives*

In Arabic, the stimuli set, made up of nouns, verbs, and adjectives both with and without vowel diacritics, was presented to the patient. The distribution of ZT's reading errors for the three grammatical classes reported in Table 2 shows that in stimuli **wo** the error rate varies with the grammatical class of the stimuli in the following way: error rate on verbs (60/64 = 94%) > error rate on nouns (117/166 = 70%) > error rate on adjectives (36/56 = 64%); the difference in the percentage of errors is significant between verbs and nouns ($\chi^2 = 12.82$, $P < 0.001$), between verbs and adjectives ($\chi^2 = 14.42$, $P < 0.001$) but not between adjectives and nouns. A similar pattern of errors is observed in stimuli **w**: more errors on verbs (60/64 = 94%) than on nouns (109/158 = 69%) ($\chi^2 = 14.03$, $P < 0.001$), more errors on verbs (94%) than on adjectives (35/56 = 62%) ($\chi^2 = 15.84$, $P < 0.001$), and no significant difference in error rate between nouns and adjectives.

The French stimuli set was made up of 40 verbs, 40 nouns and 40 adjectives matched for lexical frequency and length in number of syllables. Analysis revealed no significant grammatical class effect, but as can be seen in Table 2, the error rate distribution shows a tendency towards nouns and adjectives being read better than verbs.

5.4.6. Reading aloud of nonwords

Two lists of 63 and 22 Arabic nonwords, respectively without and with diacritics, were presented to the patient. Nonwords were created by changing one to two phonemes in real words and respected the phonotactic constraints of the language. ZT failed to produce any correct responses in reading aloud nonword stimuli presented with vowel diacritics. He could read only three nonwords without diacritics.

In French, a set of 84 nonwords controlled for phonological complexity, and length in number of letters, syllables and phonemes (see Béland, Bois, Seron, & Damien, 1999) was presented to the patient. He produced 74 errors for an error rate of 88%.

5.4.7. Distribution of error types in reading aloud

An analysis of the errors produced on words and nonwords was conducted. All stimuli used in the reading aloud tests and those used in early language assessment were included in this analysis. As indicated in Tables 3 and 4, 16 error types were identified: circumlocution, gestural, morphological, morphological-then-translation, no response, other, phonological, semantic, semantic-then-translation, translation, visual/phonological, visual/phonological-and-semantic, visual/phonological (root), visual/phonological-then-morphological, visual/phonological-then-semantic, and visual/phonological-then-translation. Examples and definitions of error types are presented in Appendix A.

Table 3
Correct responses and error distribution in word reading aloud in Arabic **wo** and **w** and in French

Response type	Arabic **wo** ($n = 610$)		Arabic **w** ($n = 277$)		French ($n = 553$)	
	No.	%	No.	%	No.	%
Circumlocution	5	0.82	2	0.72	15	2.71
Correct	219	35.90	74	26.71	200	36.17
Gestural	0	0	0	0	5	0.90
Morphological	81	13.28	56	20.22	24	4.34
Morphological-then-translation	3	0.49	1	0.36	1	0.18
No response	66	10.82	27	9.75	29	5.24
Other	20	3.28	11	3.97	10	1.81
Phonological	36	5.90	21	7.58	96	17.36
Semantic	62	10.16	28	10.11	86	15.55
Semantic-then-translation	24	3.93	14	5.05	1	0.18
Translation	29	4.75	11	3.97	8	1.45
Visual/phonological	58	9.51	31	11.19	55	9.95
Visual/phonological-and-semantic	0	0	0	0	9	1.63
Visual/phonological (root)	2	0.33	0	0	0	0
Visual/phonological-then-morphological	0	0	0	0	1	0.18
Visual/phonological-then-semantic	0	0	1	0.36	11	1.99
Visual/phonological-then-translation	5	0.82	0	0	2	0.36

Table 4
Correct responses and error distribution in nonword reading aloud in Arabic **wo** and **w** and in French

Response type	Arabic **wo** ($n = 63$)		Arabic **w** ($n = 22$)		French ($n = 84$)	
	No.	%	No.	%	No.	%
Correct	3	4.74	0	0	10	11.90
No response	32	50.56	15	68.18	11	13.09
Other	3	4.74	0	0	3	3.57
Phonological	6	9.48	2	9.09	34	40.47
Visual/phonological	16	25.28	4	18.18	22	26.18
Visual/ phonological-and-semantic	0	0	0	0	1	1.19
Visual/ phonological-then-morphological	0	0	0	0	1	1.19
Visual/phonological-then-semantic	2	3.16	1	4.54	2	2.38
Visual/phonological-then-translation	1	1.58	0	0	0	0

It should be pointed out here that most of the error types mentioned above have been reported as characterizing deep dyslexia except for the translation type which has been observed in only one deep dyslexic bilingual patient (Byng et al., 1984).

The percentage of correct responses in Arabic, reported in Table 3, is significantly higher for words presented without than with vowel diacritics ($\chi^2 = 6.85, P < 0.01$).

5.4.8. Summary

As has been suspected in ZT's early language testing, his performance in reading aloud displays the features of the deep dyslexia syndrome in both languages. Results obtained in the various reading tasks revealed that ZT's reading aloud is impaired at the sub-lexical (letters and syllables) and the lexical (words) levels. Some of the lexical effects that characterize deep dyslexic reading are found in both languages, whereas others are present in one language only. The concreteness effect (concrete words read better than abstract words), the function word effect (more errors on function words) and the lexicality effect (reading of nonwords almost impossible) are observed in both his languages. The grammatical class effect (nouns and adjectives read better than verbs) is found only in Arabic.[3]

[3] One of the reviewers drew our attention to the fact that nouns are read better than verbs in Arabic only. This may represent the first documented case in which the grammatical class effect is restricted to a specific language in a bilingual aphasic subject. We attribute ZT's poor performance in Arabic verbs to the heavy morphological load characterizing Arabic verbs; indeed, Arabic verbs are marked for aspect, person, gender and number whereas adjectives and nouns carry only gender and number morphological markers. Aphasic Arabic speakers have already been reported as experiencing difficulties with verbs, which they tend to simplify through the process of affix omission (Mimouni & Jarema, 1997).

Moreover, the results show a better performance in reading Arabic **wo**. The higher error rate in Arabic **w** may be due to the low frequency effect – Arabic speakers are trained to read in deep orthography at an early age (about 9), thus developing the addressed routine, which might be less vulnerable to language impairment.

As indicated in Table 3, the error types characterizing deep dyslexia are observed in the two Arabic orthographies. The pattern of error distribution is also similar in both orthographies. More specifically, semantic errors occur with the same proportion in both orthographies, thus refuting the prediction that more semantic errors should occur when reading deep orthography.

5.5. Semantic processing

Three different sources have been reported as being responsible for semantic errors in deep dyslexia, namely, impairment affecting access to the semantic system from visual print (input form), impairment to the semantic system itself (central form), or impaired access to phonology from the semantic system (output form). The input form of deep dyslexia is characterized by a higher proportion of visual over semantic errors and a better comprehension of spoken than written words; the central form is characterized by a higher proportion of semantic over visual errors and a poor comprehension of both spoken and written words; finally, in the output form, the proportion of semantic errors is higher than that of visual errors whereas comprehension is good for spoken and written words.

To further investigate the presumption that the patient presented the output form of deep dyslexia, the patient's semantic processing was assessed in both languages by resorting to written and auditory word–picture matching tasks and a task testing his morpho-semantic judgment from visual input.

5.5.1. Auditory word–picture matching

The patient was tested with an Arabic translation of the auditory word–picture matching test from the Caplan and Bub (1990) Psycholinguistic Assessment of Language (PAL) battery comprising 60 stimuli. In this task, the patient had to choose one of two pictures as a match to the spoken word. His score was almost perfect (59/60). Furthermore, the patient's performance in the auditory word–picture matching of the Paradis (1991) Bilingual Aphasia Test (BAT) battery was flawless (18/18).

In French, an adaptation of the PAL was used. The patient produced only one error (score = 59/60).

5.5.2. Written word–picture matching

The list of stimuli used in this task was a written adaptation of the PAL battery. The patient had to choose one of two pictures that matched the written word presented to him. He scored 50/54 (93%) and 55/60 (92%) in Arabic and French, respectively.

5.5.3. Morpho-semantic judgment

As indicated in Table 3, ZT produced a high proportion of morphological errors. This proportion is even higher in Arabic. Given that in both Arabic and French, morphologically related words are also semantically related (refer to linguistic description above), it is impossible to know whether morphological errors are triggered by the semantic or the morphological similarity of words. There are also, in both languages, words that are visually and phonologically related without being morphologically related. To assess ZT's ability to discriminate between morphologically related words and visually/phonologically related pairs, a morpho-semantic test was designed and administered. The patient was presented with three words: two were morphologically *and* semantically related whereas the third one was visually/phonologically related *only* (e.g. in Arabic: برد [barada] 'to cool'; برودة [buruuda] 'the cold'; بريد [bariid] 'mail'; in French: *greffer* 'to transplant', *greffon* 'transplanted organ', and *greffier* 'legal clerk'). The patient was requested to identify the word that was not morphologically related. The stimuli consisted of 24 triads in Arabic presented without diacritics and 72 triads in French. The patient's score was 15/24 (62.5%) and 59/72 (82%) in Arabic and French, respectively. The performance of three Arabic/French bilingual control subjects and of six French-speaking control subjects matched for age and educational level was almost flawless on this test. In Arabic, the three bilingual controls produced two, four and three errors for a mean performance of 21/24 (87.5%). In French, four of the controls produced no errors and two produced three errors for a mean score of 71/72 (98.6%).

5.5.4. Summary

The present results show that ZT's semantic processing is mildly impaired. From ZT's performance in word–picture matching, one may conclude that the semantic errors in reading result from an impairment in the retrieval of the phonological representation subsequent to correct activation of the concept in the semantic system, pointing to an output form of deep dyslexia.

5.6. Sub-lexical processing

A characteristic of deep dyslexic patients is their inability to derive phonology from print sub-lexically. French has a deep writing system whereas Arabic has, to some extent, a less deep writing system since consonantal graphemes have one and only one sound correspondence, a feature that rules out the possibility of constructing a rhyme judgment task in the language. Word endings of rhyming words being necessarily spelled the same way in Arabic, the derivation of phonology is not needed to perform the task, and thus, a rhyming task in Arabic is no different from a discrimination task. For this reason, rhyme judgment was tested only in French.

5.6.1. Rhyme judgment from auditory input

The stimuli set comprised 116 pairs of words subdivided into four categories: (1) word pairs with homographic non-rhyming endings (e.g. *aquarium* [akwariɔm] 'aquarium' vs. *parfum* [parfœ̃] 'perfume'); (2) word pairs with heterographic non-rhyming endings (e.g. *gâteau* [gato] 'cake' vs. *tiroir* [tirwar] 'drawer'); (3) word pairs with homographic rhyming endings (e.g. *souper* [supe] 'supper' vs. *laver* [lave] 'to wash'); and (4) word pairs with heterographic rhyming endings (e.g. *balai* [balɛ] 'broom' vs. *sommet* [sɔmɛ] 'summit'). Therefore, in this rhyming test, half of the *yes* and half of the *no* responses corresponded to homographic stimuli, whereas the other half corresponded to heterographic stimuli. The patient was requested to answer *yes* if the word endings in the pairs rhymed and *no* if they did not. If the patient's judgment were to be based solely on word spelling, then the patient should be 100% correct in categories (2) and (3) and 100% incorrect in categories (1) and (4).

ZT obtained the following scores in each of the categories: (1) 21/29 (72%) (e.g. *aquarium* [akwariɔm]–*parfum* [parfœ̃]); (2) 27/29 (93%) (e.g. *gâteau* [gato]–*tiroir* [tirwar]); (3) 21/29 (72%) (e.g. *souper* [supe]–*laver* [lave]); and (4) 16/29 (55%) (e.g. *balai* [balɛ]–*sommet* [sɔmɛ]). Mean scores of the three bilingual (Arabic/French) controls were (1) 28.33/29 (98%), (2) 28.65/29 (99%), (3) 24.45 (88%), and (4) 21.33/29 (73%).

5.6.2. Rhyme judgment from visual input

The stimuli set comprised 108 word pairs taken from the set of pairs used in the auditory rhyme judgment task. The distribution of the number of pairs for each category was the following: 26 pairs in category (1), 27 pairs in category (2), 29 pairs in category (3), and 26 pairs in category (4). The patient was requested to answer *yes* if the word endings in the pairs rhymed and *no* if they did not.

ZT obtained the following scores: (1) 9/26 (35%); (2) 22/27 (81%); (3) 15/29 (52%); and (4) 3/26 (12%). The mean scores of the three bilingual (Arabic/French) controls were (1) 22.11/26 (85%), (2) 27/27 (100%), (3) 28.03/29 (97%) and (4) 18.22/26 (70%).

5.6.3. Summary

ZT's overall performance in rhyme judgment was significantly worse in the visual input modality (49/108 = 45%) than in the auditory modality (85/116 = 73%), suggesting an impaired sub-lexical access to phonology from orthography. This could result from his impairment in verbal working memory. Note that his performance in rhyme judgment from both auditory and visual input is worse than that of the controls even though it shows a similar trend with the control subjects (highest score on category (2) and lowest score on category (4)). However, the discrepancy observed in the results across categories, which was also observed in bilingual control subjects, is an indication that orthography has an effect on performance in auditory as well as visual rhyme judgment.

Results from reading aloud and visual rhyme judgment tasks indicate an impaired access to phonology from orthography at both lexical and sub-lexical levels. The question that arises now is whether access to phonology from the semantic system is impaired (pathway F-D in Fig. 3). A picture-naming task was designed to this effect.

Table 5
Correct responses and error distribution in oral naming of 100 picture stimuli in Arabic and in French

Response type	Arabic ($n = 100$)	French ($n = 100$)
Correct	34	62
No response	1	0
Circumlocution	1	0
Gestural	0	1
Morphological	2	0
Other	6	2
Phonological	1	2
Semantic	22	28
Semantic-and-phonological	0	1
Semantic-then-translation	11	2
Translation	22	2

5.7. Oral picture naming

A set of 100 pictures was used in this task. As illustrated in Table 5, the patient made semantic errors in both languages, an indication that pathway F is impaired.

5.8. Repetition

Semantic errors produced in reading and those produced in picture naming seem to result from an impaired retrieval of the phonological representation subsequent to a correct activation of the concept in the semantic system. However, the presence of phonological errors observed in both reading and picture naming is an indication that there might be impairment to the phonemic output buffer. To further investigate this possibility, repetition and delayed repetition tasks were designed.

5.8.1. Immediate repetition

ZT was tested in immediate repetition for the concreteness effect (concrete vs. abstract words), the function word effect (function words vs. open class items), the grammatical class effect (verbs, nouns, and adjectives) and the lexicality effect (words vs. nonwords). The results summarized in Table 6 show that ZT's error rate is low in both Arabic (21/396 = 5.3%) and French (15/240 = 6.25%) in word repetition; the difference is not significant. The errors collected in Arabic and French were either morphological, phonological or phonological/lexical.

The results show no effect of concreteness, function word or grammatical class in any of the two languages. However, a significant lexicality effect was observed in both languages. The percentage of errors was significantly higher on nonwords than on words in both languages ($\chi^2 = 36.42$, $P < 0.001$ for Arabic; $\chi^2 = 8.98$, $P < 0.01$ for French).

According to the model in Fig. 3, this discrepancy is accounted for by refreshment of the phonological trace through pathway D-G for words. The presence of permanent representations for words in the phonological lexicon, which are not available

Table 6
Number and percentage of errors for different word categories in Arabic and French in repetition

	Arabic		French	
	No.	% errors	No.	% errors
Concreteness effect				
Concrete	0/24	0	1/30	3
Abstract	1/24	4	5/30	17
Function word effect				
Open class items	0/35	0	1/30	3
Closed class items	0/35	0	2/30	7
Grammatical class effect				
Nouns	13/160	8	1/40	3
Verbs	5/74	7	3/40	8
Adjectives	2/44	4	2/40	5
Lexicality effect				
Words	13/160	8	26/139	19
Nonwords	29/67	43	23/57	40

for nonwords, contributes to the phonological output processing by allowing a refreshment of the acoustic input trace through pathway G. A refreshment of the trace through pathway D-G should be even more important in a delayed repetition task, and consequently, the resulting phonological activation could propagate to the semantic system through pathway H. Since the semantic output pathway F is impaired, semantic errors are expected to occur in delayed repetition. Furthermore, an increase in the delay should produce an increase of semantic errors.

5.8.2. Delayed repetition

Two sets of 120 and 124 word stimuli were used in Arabic and French, respectively. The patient was requested to repeat a word only after he had finished counting silently from one to five in the 5 s repetition delay and from one to ten in the 10 s repetition delay. In Arabic, ZT produced 36 errors out of 120 stimuli (30%) in the 5 s delay and 26 errors (22%) in the 10 s delay. In French, ZT produced 27 errors out of 124 stimuli (22%) in the 5 s delay and 24 (19%) in the 10 s delay. The difference in scores between the two delays is not significant in either of the languages. The error distribution for both delays is presented in Figs. 4 and 5.

Semantic errors were produced in both languages in the two tasks. The increased delay results in a lower rate of semantic errors in Arabic (Fig. 4) and in a higher rate in French (Fig. 5). In contrast, phonological errors increase in Arabic but decrease in French. Although these differences are not significant, mainly because of the low number of errors, it is worth pointing out that there is a trend toward a double dissociation. According to predictions by Knott, Patterson, and Hodges (1997) on DTA patients with semantic dementia, the increase of semantic errors in French following the increase in the delay would be an indication of a deficit in phonological access. On the other hand, the increase of phonological errors following the

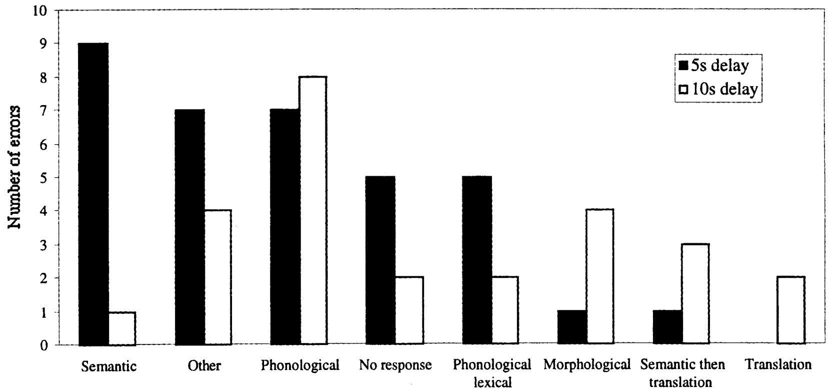

Fig. 4. Error distribution in delayed repetition in Arabic for short (5 s) and long (10 s) delays.

increase in the delay may be a result of trace degradation. An interpretation of this double dissociation is presented later within the connectionist approach.

5.8.3. Summary

The presence of semantic errors in reading aloud, delayed repetition and oral picture naming in the presence of a partially impaired semantic system suggests an impairment in accessing the phonological lexicon from the semantic system (pathway F in Fig. 6). Errors in auditory and visual LDTs indicate impairment to pathways B and I.

ZT's preserved comprehension of the words he read correctly and of those he read with semantic errors is an indication that the patient is not relying on pathway C for reading, a route generally assumed to be damaged in deep dyslexic readers. Errors in nonword reading and in nonword repetition are an indication of impairment to the phonemic output buffer. The above five lesions are indicated in Fig. 6 by large Xs.

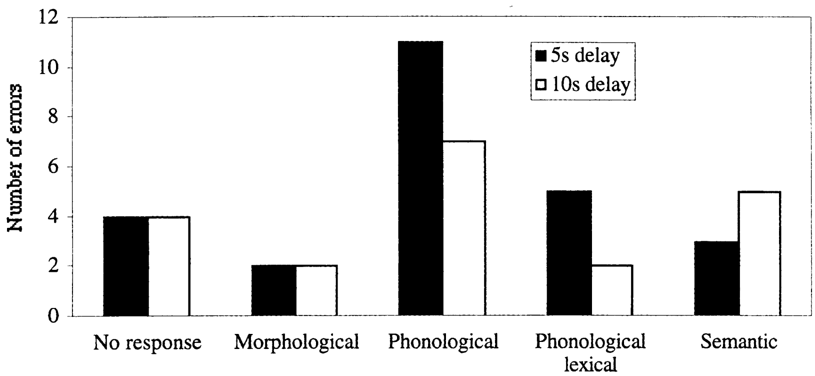

Fig. 5. Error distribution in delayed repetition in French for short (5 s) and long (10 s) delays.

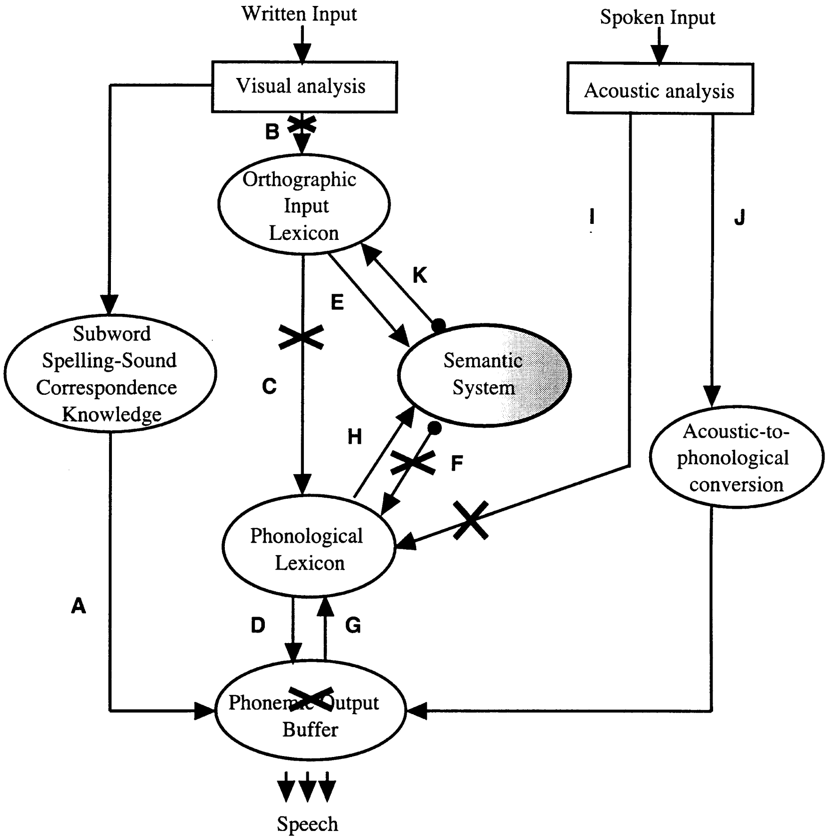

Fig. 6. The functional lesions typically found in output deep dyslexic patients.

The shaded area in the semantic system represents the partial impairment observed in abstract word reading and morpho-semantic judgment.

The lesions in pathways C and F and the lesion to the phonemic buffer correspond to the typical lesions found in output deep dyslexic English-speaking patients (JA in Katz & Lanzonni, 1992; GR in Hildebrandt & Sokol, 1993; JC in Buchanan et al., 1994; and LW in Newton & Barry, 1997). In three of the four reported output dyslexic cases, authors aimed to demonstrate that implicit (automatic) access to the sub-lexical phonology of words (JA and CR) and nonwords (JC) is preserved in output deep dyslexia. Buchanan et al. (1994) reported that their patient JC showed significant phonological priming effects in a visual LDT. The patient's reaction times (RTs) were faster when the word stimuli were preceded by a homophonous nonword than when they were preceded by a non-homophonous nonword. For instance, JC showed a priming effect, that is, shorter RTs when 'chair' was preceded by the pseudohomophone "taybul" than when the same target was preceded by the orthographic control "tarble". The authors interpreted the priming effect they obtained as an indication that assembled phonological recoding through pathway A may not be abolished in output deep dyslexia.

In the case of our patient, performance in nonword reading aloud was very poor, indicating that explicit phonological recoding was not possible. However, ZT's implicit assembled phonological recoding from visual input may be preserved. A well-suited task to investigate an implicit access to nonword phonological recoding is a visual LDT within a cross-language phonological priming paradigm.

5.9. Cross-language phonological priming

As mentioned earlier, Arabic and French have highly contrastive writing systems but their phonemic inventories share 14 consonants and three vowels. It was, therefore, possible to construct cross-language quasi-homophonous pairs (the phonemes coming from different phoneme inventories, the pairs are not totally homophonous), that is, pairs in which a nonword-prime and a word-target are written in different languages and show phonological similarity without orthographic similarity. A priming effect, that is, shorter RTs in homophonous pairs than in non-homophonous pairs, could be obtained only if there is a phonological recoding of the visual nonword-prime.

Two visual LDTs within a cross-language phonological priming paradigm were designed. In LDT1, targets were written in French and primes in Arabic **wo**. In LDT2, targets were written in Arabic **wo** and primes in French. In both LDTs, the priming effect was measured by comparing RTs in phonologically related pairs (cross-language homophonous pairs: e.g. "calbée" – كلب 'dog') with RTs in phonologically unrelated pairs (pairs in which primes from related pairs were replaced by non-homophonous nonwords: e.g. "beurli" – كلب 'dog'). Related and unrelated pairs were included in two separate testing conditions (experimental and control, respectively), and administered in two separate sessions within a 1 month interval. Stimuli were presented **wo** except in three words where the vowel diacritics were provided to avoid semantic confusion with homographic counterparts.

5.9.1. LDT1: Arabic nonword-prime/French word-target

5.9.1.1. Design and material. In the experimental condition, the stimuli set consisted of 108 pairs in which the prime was an Arabic word or nonword and the target was a French word or nonword. The 36 related pairs consisted of homophonous items (Arabic nonword/French word: شاز [ʃɛz]–*chaise* [ʃɛz] 'chair'). The remaining 72 pairs were Arabic/French non-homophonous fillers (18 nonword/nonword pairs, 18 word/nonword pairs, and 36 word/word pairs). In the 108 trials, 72 corresponded to *yes* responses and 36 to *no* responses. Among the 72 *yes* responses, 36 were preceded by a word-prime and 36 by a nonword-prime. Among the 36 *no* responses, 18 were preceded by a nonword-prime and 18 by a word-prime. Thus, the lexical decision (yes–no) could not be based on the lexical status of the prime, since half of the nonword-primes were followed by a word-target and half were followed by a nonword-target.

In the control condition, the 36 related pairs were replaced by 36 unrelated pairs in which the prime was a non-homophonous nonword. All other pairs remained the same.

5.9.1.2. Procedure. The experiments were run on a computer using the Psychlab software package (Bub & Gum, 1988). Stimuli were presented in the middle of the display screen. For each trial, primes appeared for 500 ms. They were replaced by the targets, which remained on the screen until the subject gave a response. The stimuli interval was 50 ms. The patient was instructed to be fast and to press the right shift key whenever he recognized a word and to press the left shift key otherwise. A training session consisting of 12 trials, which were not part of the stimuli sets, preceded the testing sessions.

5.9.1.3. Results. RTs for correct responses in the related and unrelated pairs appear in Table 7. Three standard deviations on either side of the mean were removed prior to analysis, and only responses that were correct in both the experimental and the control conditions were considered. This resulted in the loss of nine pairs. An ANOVA taking into account pair types (four different types) and testing conditions (experimental vs. control) reveals a significant testing condition effect ($F(1,85) = 6.53$, $P < 0.05$) and a significant interaction between testing condition and pair type ($F(3,85) = 7.20$, $P < 0.001$). Decomposition of the interaction reveals a significant testing condition effect in the word/nonword filler type only ($F(1,85) = 18.25$, $P < 0.001$). Mean RTs for filler types are significantly longer in the control testing condition (mean RTs = 1131 ms) than in the experimental testing condition (mean RTs = 899 ms). RTs for correct *yes* responses to nonword/word pairs were entered in a paired *t*-test. As indicated in Table 7, ZT showed no significant priming effect. The difference in mean RTs between related and unrelated pairs was not significant ($t(26) = 0.88$, $P = 0.18$). These results do not show implicit assembled phonological recoding (through pathway A in Fig. 6) for Arabic nonwords, but they do not rule out the possibility of an implicit access for French nonwords.

5.9.2. LDT2: French nonword-prime/Arabic word-target

5.9.2.1. Design and material. In the experimental condition, the stimuli set consisted of 129 pairs in which the prime was a French word or nonword and the target was an Arabic word or nonword. Thirty-four related pairs consisted of homo-

Table 7
Results of cross-language phonological priming in LDT1 and LDT2

	LDT1 mean RTs (ms)	LDT2 mean RTs (ms)
Related pairs	1047	1034
Unrelated pairs	1014	1198
P value	> 0.05	< 0.05

phonous experimental items (French nonword/Arabic word: “calbée” [kalbe]/كلب [kalbe] ‘dog’). The remaining 95 pairs were French/Arabic non-homophonous fillers (29 nonword/nonword pairs, 35 word/nonword pairs, and 31 word/word pairs). In the 129 trials, 65 corresponded to *yes* responses and 64 to *no* responses. Among the 65 *yes* responses, 34 were preceded by a word-prime and 31 by a nonword-prime. Among the 64 *no* responses, 29 were preceded by a nonword-prime and 35 by a word-prime. Thus, the lexical decision (*yes–no*) could not be based on the lexical status of the prime, since half of the nonword-primes were followed by a word-target and half were followed by a nonword-target. In the control condition, the 34 related pairs were replaced by 34 unrelated pairs. All other pairs remained the same.

5.9.2.2. Procedure. The same procedure as in LDT1 above was followed.

5.9.2.3. Results. RTs for correct responses in the experimental and the control trials appear in Table 7. Three standard deviations on either side of the mean were removed prior to analysis, and only responses that were correct in both the experimental and the control conditions were considered. This resulted in no loss of responses. An ANOVA examining the effects of pair types (four different types) and testing conditions (experimental vs. control) on RTs reveals a significant interaction between testing condition and pair type ($F(3, 125) = 5.46$, $P < 0.001$). Decomposition of the interaction reveals a significant testing condition effect for the word/nonword filler type ($F(1, 125) = 11.6$, $P < 0.001$) and the nonword/word pair type ($F(1, 125) = 4.74$, $P < 0.05$). Mean RTs for word/nonword fillers are shorter (mean RTs = 1029 ms) in the control than in the experimental condition (mean RTs = 1282 ms). RTs for correct *yes* responses to nonword/word pairs were entered in a paired *t*-test. As indicated in Table 7, mean RTs in related pairs were shorter than mean RTs in unrelated pairs ($t(33) = -2.20$, $P = 0.017$).

An absence of priming in LDT1 shows that there is no implicit assembled phonological recoding for Arabic nonwords. This may be a result of the difficulty ZT has in establishing spelling-to-sound correspondence, or the failure of the phonological activation in producing a priming effect. To account for the priming effect observed between a visual French nonword and a visual homophonous Arabic word in LDT2, given the functional lesions indicated in Fig. 6, two interpretations may be put forward.

(1) ZT first assembles the phonology of the written French nonword through pathway A (see Fig. 6). The resulting phonological activation via pathway G is sufficient to activate the phonological representation of the homophonous Arabic word, which implies that the two phonological representations are in some way linked. Then, the semantic representation of the Arabic word is activated through pathway H. Finally, the written Arabic target appears and is read via the semantic pathway B-E. Pre-activation in the semantic system is responsible for reduced RTs.

(2) ZT first assembles the phonology of the written French nonword through pathway A. The resulting phonological activation via pathway G is sufficient enough to activate the phonological representation of the homophonous Arabic word, which

in turn activates the semantic representation of the Arabic word through pathway H, then up to the orthographic lexicon via pathway K. When the written Arabic target appears, it is read through mildly impaired pathway B. Pre-activation in the orthographic lexicon is responsible for reduced RTs.

5.10. Interpretation of ZT's impairments within a three-route model

As reported in Table 3, ZT's performance in reading shows most of the features of deep dyslexia. Furthermore, 13 of the 16 error types were found in both languages. Within the multi-impairment approach, ZT's overall linguistic deficit can be accounted for by positing two sets of lesions, each affecting separate monolingual architectures.

A set of six lesions for each language is required to explain all of the impairments observed. First, ZT's various errors in reading, naming and delayed repetition could be explained as resulting from lesions to the phonological output component itself, to the activation of the phonological lexicon by the semantic system and to the non-semantic lexical route. The concreteness effect in reading and the low performance in the morpho-semantic judgment task are indications that the semantic system itself is partially impaired. Finally, lesions to pathways B and I could be postulated to account for the presence of errors in visual and auditory lexical decisions.

Furthermore, given that the qualitative analysis showed similar deficits in the two languages of the patient, one should conclude to similar lesions sites in the functional architectures corresponding to Arabic and French. Taken together, the lesions responsible for ZT's impairments in the two languages amount to 12, a large number indeed.

However, even if the phonological priming obtained in LDT2 leads us to propose links between the two phonological lexicons, and this proposal reduces the number of lesions responsible for deep dyslexia in bilingual subjects, this number would still range between six and 12, depending on the quantity of shared components and pathways among the two monolingual architectures. We find this explanation somehow unattractive.

A further weakness of the multi-impairment approach lies in its inability to account for the discrepancy observed in error distribution across languages. As indicated in Tables 3 and 5, the semantic error rate is higher in French, whereas the translation error rate is higher in Arabic. To explain the higher semantic error rate in picture naming and reading aloud in French compared to Arabic, one should postulate that the lesion along pathway F is more severe in French than in Arabic. On the other hand, the higher translation error rate in Arabic as opposed to French should be explained by positing that pathway F linking access to the French phonological lexicon from the semantic system is less impaired than the corresponding pathway for Arabic. ZT's tendency to translate from Arabic to French is indeed a clear indication that the mapping between the semantics and the French phonology along pathway F is unimpaired.

Furthermore, since there was no significant difference in error rate and in error distribution between the two languages in the task of immediate word repetition, the dissociation across languages cannot be accounted for by positing a lesion to the components located downstream of pathway F, namely in the phonological lexicon itself or in the transfer to the phonemic buffer.

To conclude, the multi-impairment approach to bilingual deep dyslexia is unparsimonious and does not provide an explanation for the dissociation found across languages in error distribution.

An alternative to the three-route model is the connectionist approach to deep dyslexia. Plaut and Shallice (1993) have conducted simulations of deep dyslexia, which have resulted in quantitative evaluations of error distribution, overall performance and error types according to lesion sites and lesion severity. In the following section, we will attempt an interpretation of ZT's reading impairment within the Plaut and Shallice (1993) model, which we will refer to as the P & S model. We will first propose accommodations to this model to account for bilingual deep dyslexic patients and then compare ZT's error distribution to that obtained by Plaut and Shallice after lesioning the 40–60 network.

6. Interpretation of ZT's impairment within a connectionist model

6.1. Accommodations to the Plaut and Shallice (1993) model to account for translinguistic errors

As briefly stated, Plaut and Shallice (1993) accounted for the deep dyslexia syndrome by lesioning a connectionist model which maps orthography to phonology through semantics. Lesions to different parts of this network result in the same overall syndrome. At the same time, aspects of the syndrome differ between lesion sites. Therefore, this model might be the appropriate tool to account for the overall syndrome of output deep dyslexia observed in both ZT's languages, as well as to explain the discrepancies observed across tasks and languages. Before comparing ZT's error pattern to that obtained by Plaut and Shallice after lesioning the 40–60 network, we propose extensions to their network in order to accommodate for deep dyslexia in bilingual subjects.

An important concept from the Hinton and Shallice (1991) model that Plaut and Shallice (1993) and Plaut (1997) reintroduced is that of the *attractor*, i.e. the final stable pattern of activity resulting from interactions in the network between input units and network units when processing a word, or as defined by Plaut (1997, p. 2), "In processing an input unit, units interact until the network as a whole settles into a stable pattern of activity – termed an *attractor* – corresponding to its interpretation of the input." The co-occurrence of visual and semantic errors in deep dyslexia is the result of a damaged network that builds attractors in mapping two arbitrarily related domains. As reproduced in Fig. 7, in Hinton and Shallice's network the visual error (CAT → COT) is explained as follows: the words CAT and COT which are visually similar build similar initial large basins of attraction in the semantics.

As indicated by the arrows in the semantics component, the effect of the learning procedure is to pull the two distinct meanings apart. In a damaged network, the

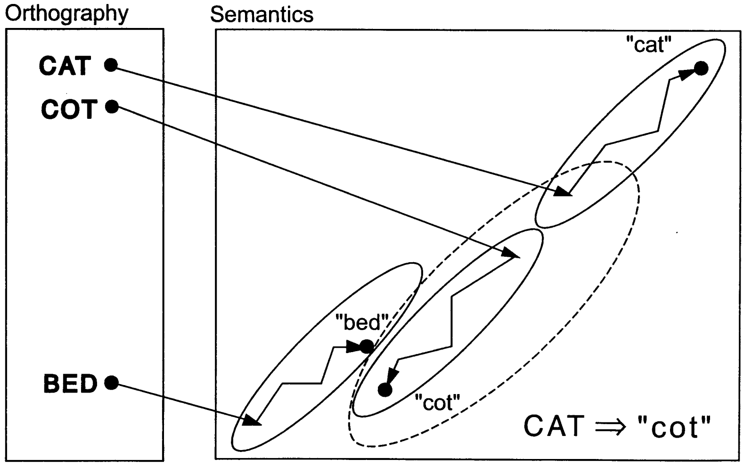

Fig. 7. Illustration of the visual error CAT → COT. The solid ovals depict the normal basins of attraction; the dotted ones depict a basin after semantic damage. Plaut & Shallice (1993), Deep dyslexia: a case study of connectionist neuropsychology. *Cognitive Neuropsychology*, 10 (5) p. 393. Reprinted by permission of Psychology Press Ltd., Hove, UK.

original attractor basins (represented by solid ovals in Fig. 7) are distorted and enlarged (dotted basin in Fig. 7) such that the semantic pattern of CAT is captured into the basin of the visually similar word COT. Thus, within this approach, visual and semantic errors co-occur because the layout of attractor basins is sensitive to both visual and semantic similarity (Plaut & Shallice, 1993, p. 394). However, the layout of attractor basins as developed in Hinton and Shallice (1991) and in Plaut and Shallice (1993) does not account for bilingual subjects and hence, requires some accommodations.

In both Arabic and French, the links between orthography and semantics are arbitrary. In addition, the two languages contain words that are visually similar but semantically unrelated (e.g. French: *matelas* 'mattress' vs. *matelot* 'sailor'; Arabic: بريد 'mail' vs. برد 'cold') as well as words that are semantically related but visually unrelated (French: *rose* 'rose' vs. *fleur* 'flower'; Arabic: وردة 'rose' vs. زهرة 'flower').

In French, words that are phonologically similar are not necessarily visually similar (e.g. *biais* 'bias' vs. *billet* 'ticket'). In Arabic, given the high regularity in spelling-to-sound correspondence, words that are visually similar are phonologically similar as well (e.g. Arabic إشاعة 'rumor' and ساعة 'a watch'). Consequently, it is impossible to determine whether the layout of attractor basins is sensitive to visual and semantic similarity or to phonological and semantic similarity. Since the Hinton and Shallice (1991) model does not include the mapping from semantics to phonology, the accommodations we are proposing are limited to the links between orthography and semantics (Fig. 7).

Our proposal is that the building of attractor basins for Arabic/French bilingual subjects proceeds as proposed by Hinton and Shallice (1991) except that the training procedure involves the building in semantics of attractor basins linked to two orthography and two phonology components. The attractor basins in French represent a disjunctive set of the Arabic attractor basins since words that are visually or phonologically similar in French (e.g. *salade* 'salad'–*sandale* 'sandal') are not mandatorily visually or phonologically similar in Arabic (e.g. سلطة 'salad'; 'sandal' نعل), and as a matter of fact, an Arabic word cannot be visually similar to a French word since the two languages have different alphabets.

The link between the two languages lies in the semantics: words that are semantically related in Arabic are also semantically related in French. This extension of attractor basins for bilingual subjects allows us to account for a number of translinguistic errors produced by ZT. We distinguish four types of translinguistic errors: (1) translation (the patient's response is given in the other language rather than in the language of testing); (2) visual-then-translation; (3) semantic-then-translation; and (4) translation-then-visual/phonological (see Appendix A).

6.1.1. Translation errors

Translation errors are the most easily explained errors within the bilingual network we are proposing. As illustrated in Fig. 8, a translation error (Arabic نظارات 'glasses' read as French *lunettes* 'glasses') occurs when the semantic representation of a word is erroneously captured into the attractor basins of the other language. Thus, such errors, which occur because the two languages build attractor basins that are semantically related, should be equally found in the two languages of an early bilingual patient. Moreover, they should occur in any language task involving the semantic component.

6.1.2. Visual/phonological-then-translation errors

As illustrated in Fig. 9, the visual/phonological-then-translation type of errors, such as French *portillon* 'gate' read as فراشة 'butterfly' in Arabic, involves first a

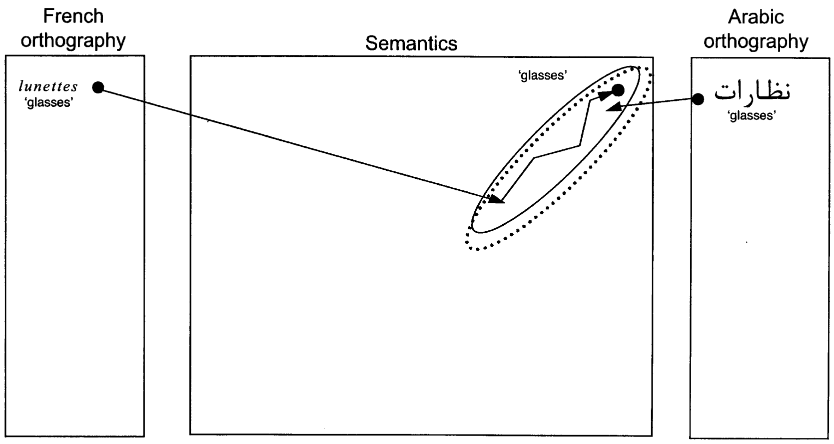

Fig. 8. Illustration of a translation error in reading aloud: Arabic نظارات 'glasses' read as French *lunettes* 'glasses'.

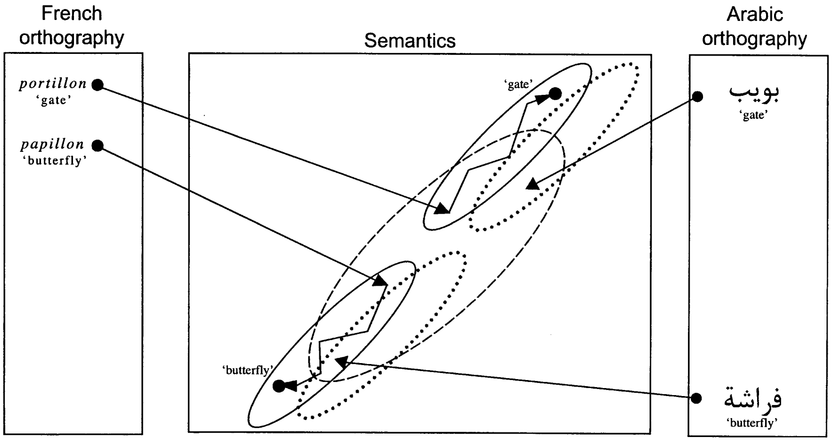

Fig. 9. Illustration of a visual/phonological-then-translation error in reading aloud: French *portillon* 'gate' read as فراشة 'butterfly' in Arabic.

visual similarity in French between *portillon* and *papillon* 'butterfly'. As in the CAT–COT example, the word *portillon* is erroneously captured into the attractor basin of *papillon* because of the enlargement of the attractor basin. From there, the semantic representation of the word is erroneously captured into the visual/phonological representation of the Arabic word for *papillon*.

6.1.3. Semantic-then-translation errors

The semantic-then-translation error type (e.g. French *éponge* 'sponge' read as بحر 'sea' in Arabic) illustrated in Fig. 10 is the semantic counterpart of the visual/phonological-then-translation error. The word *éponge* in French is erroneously captured into the attractor basin of French *mer* 'sea', which is, in turn, erroneously captured into the visual/phonological representation of that word in Arabic.

6.1.4. Translation-then-visual/phonological errors

Translation-then-visual/phonological errors are, probably, the most difficult ones to detect in that they involve the search for visual/phonological similarity in the other language. Fig. 11 illustrates a hypothetical example of this type of error predicted to occur in bilingual Arabic/French deep dyslexic patients. In this example, French *rumeur* 'rumor' is read as French *montre* 'watch'. To account for this error one should posit first that the word *rumeur* is correctly assigned to its correct meaning. From then, it is erroneously captured into the attractor basin of the Arabic equivalent إشاعة 'rumor', which is phonologically and visually similar to the Arabic word ساعة 'a watch'. Then, the correct semantic representation of the word 'watch' in Arabic is, as in simple translation errors, associated to the phonological representation of that word in French resulting in the production of the French *montre* 'watch'. The closest example found in our corpus corresponding to this type of error is French *photo* 'photo' read as French *montre* 'watch'; this example does not fit

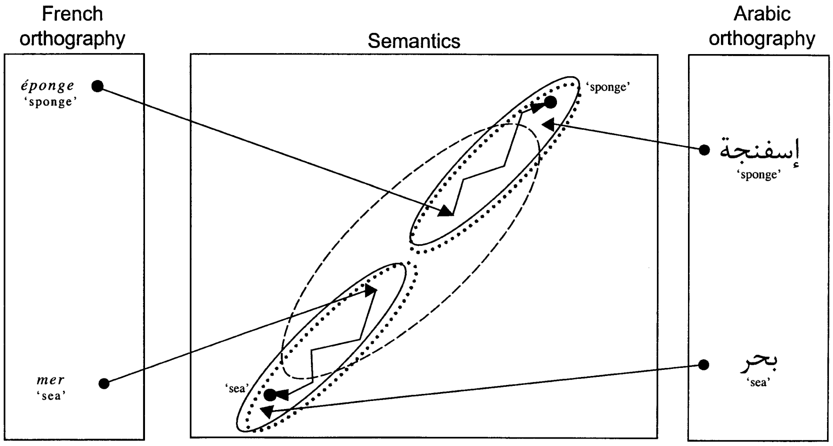

Fig. 10. Illustration of a semantic-then-translation error in reading aloud: French *éponge* 'sponge' read as بحر 'sea' in Arabic.

quite well into the present category since the Arabic word صورة corresponding to *photo* is phonologically but not visually similar to the Arabic equivalent ساعة for *montre*. We predict that this error type should logically occur in deep dyslexic bilingual patients. For instance, in a French/English bilingual patient, we expect errors such as the French word *sourd* read as *mort* given that the two words are close in English ('deaf' vs. 'death') and the other way around, the English word "bread" read as "pine" because the corresponding words *pain* and *pin* are close in French.

6.1.5. Summary

The above accommodations to the P & S model allow us to account for the

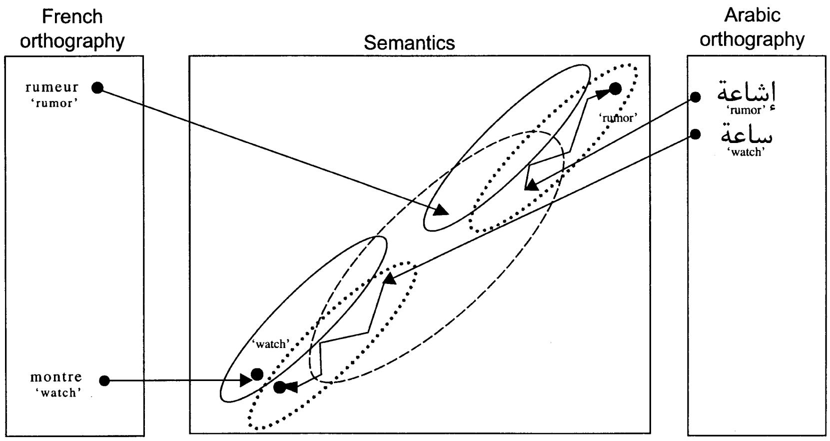

Fig. 11. Illustration of a hypothetical example of a translation-then-visual/phonological error in reading aloud: French *rumeur* 'rumor' read as French *montre* 'watch'.

occurrence of ZT's translinguistic errors. Let us now turn to ZT's overall performance in French and Arabic and compare it to that obtained by Plaut and Shallice (1993) after lesioning the 40–60 output network. Since the accommodations proposed above have not yet been implemented and no simulation of the extended network has been run, the following interpretation of the consequences on reading performance after damage to such a bilingual network is purely hypothetical.

6.2. Lesion severity and lesion sites

ZT's error distribution in reading aloud for word stimuli is given in Table 3. The percentage of correct responses is very similar in Arabic **wo** (219/610 = 35.90%) and French (200/553 = 36.17%). In the P & S model, the output form of deep dyslexia results from lesions to the direct pathway of the output network ($S \rightarrow Ip$, $Ip \rightarrow P$), more specifically, from lesions affecting the $S \rightarrow Ip$ and the $Ip \rightarrow P$ connections, i.e. the connections between the sememe units (S) and the intermediate units (Ip) in the output pathway to phoneme units, and the connections from these intermediate units to the phoneme units (P) (see Fig. 13). According to the simulations conducted (Plaut & Shallice, 1993, p. 418), a lesion with a severity of 0.3 affecting either or both output pathways $S \rightarrow Ip$ and $Ip \rightarrow P$ results in an overall correct performance between 30 and 40%, which is comparable to that observed in ZT's two languages. However, to determine whether pathway $S \rightarrow Ip$, $Ip \rightarrow P$ or both is lesioned in French and Arabic, ZT's error distribution in reading aloud must be compared to that obtained by Plaut and Shallice after selectively lesioning pathways $S \rightarrow Ip$ and $Ip \rightarrow P$. According to Plaut and Shallice (1993, p. 420) a higher semantic error rate is associated with lesions affecting the $S \rightarrow Ip$ connections, whereas a lower semantic error rate is attributed to lesions affecting the $Ip \rightarrow P$ connections. ZT's error distribution in reading word stimuli aloud in Arabic **wo** and in French is illustrated in Fig. 12. As shown, visual/phonological error rates are similar in French (55/553 = 9.95%) and Arabic **wo** (58/610 = 9.51%) ($\chi^2 = 0.23$, $P > 0.05$). The semantic error rate (see Table 3) is higher in French (86/553 = 15.55%) than in Arabic **wo** (62/610 = 10.16%); the difference is significant ($\chi^2 = 7.10$, $P < 0.01$).

It is thus possible, within a connectionist approach, to account for the difference in error distribution in the patient's two languages by positing lesions affecting different connections of the 40–60 output network. Lesions to the output pathways $S \rightarrow Ip$ and $Ip \rightarrow P$ account for the comparable visual/phonological error rate observed in the two languages. Lesions affecting mostly $Ip \rightarrow P$ connections may be responsible for a lower semantic error rate in Arabic whereas lesions affecting the $S \rightarrow Ip$ connections may explain the higher semantic error rate in French (illustrated in Fig. 13 with dotted arrows).

The morphological error rate (see Table 3) is higher in Arabic **wo** (81/610 = 13.28%) than in French (24/553 = 4.34%) and the difference is significant ($\chi^2 = 27.14$, $P < 0.001$). According to Plaut and Shallice (1993), morphological errors are a sub-variety of visual/phonological-and-semantic errors. In ZT's French error corpus, both morphological errors (e.g. *goûter* 'to taste' read as *goût* 'taste') and visual/phonological-and-semantic errors (e.g. *canari* 'canary' read as

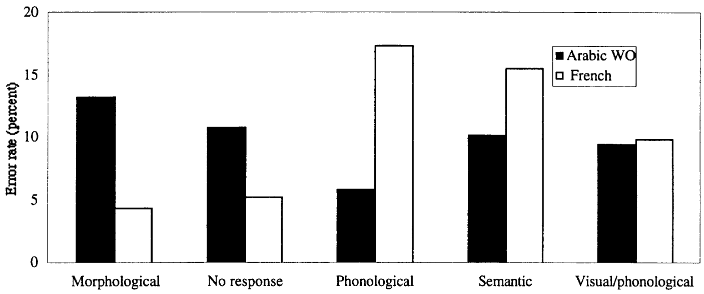

Fig. 12. Error distribution in reading aloud in Arabic **wo** ($n = 610$) and in French ($n = 553$). Error types with error rates ≥10% in either language are plotted.

canard 'duck') are found. In Arabic, only morphological errors are found. This may be accounted for by the difference in the morphological structure of the two languages. In Arabic, given the root-based structure of the lexicon, words that are visually, phonologically and semantically related are more likely to be morphologically related as well. According to this interpretation, ZT's morphological error rate is higher in Arabic because the links between morphophonology and semantics are stronger in Arabic than in French.

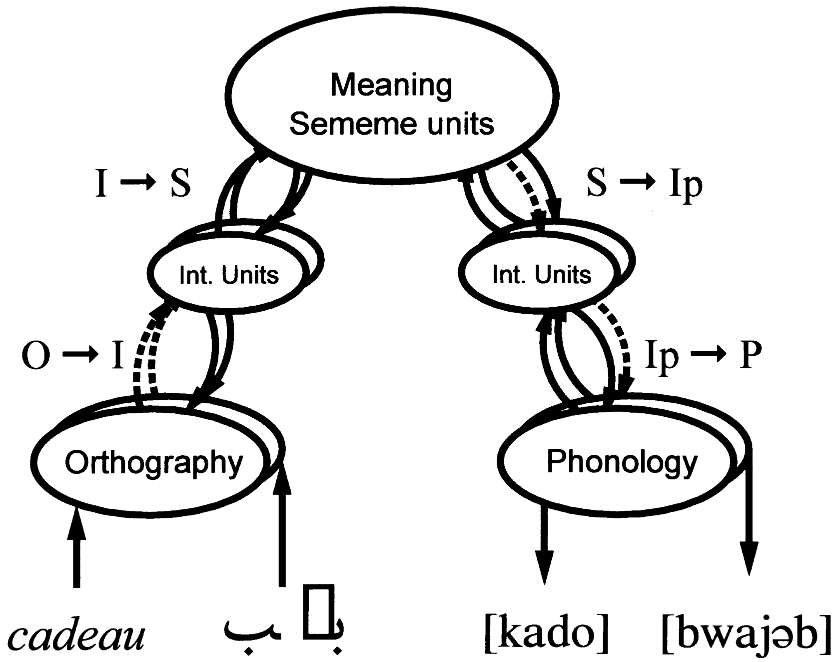

Fig. 13. Representation of the bilingual network. Dotted arrows indicate the lesioned connections: O → I in Arabic and French, S → Ip in French and Ip → P in Arabic.

6.3. Concreteness effect

As was reported earlier, when reading aloud ZT produced significantly fewer errors in concrete than in abstract words in both languages. According to Plaut and Shallice (1993), a concreteness effect results from lesions affecting the input pathway of reading (O → I or I → S). Because concrete words have more semantic features, their reading is less influenced by damage to the input pathway. Conversely, because abstract words have fewer semantic features, their reading is more likely to rely on this damaged direct pathway, thus resulting in a higher error rate.

According to Plaut and Shallice (1993, Table 11, p. 457) (the relevant information is reproduced in our Table 8), the difference in error rate between concrete and abstract words varies as a function of both lesion severity and lesion location along the direct O → I and I → S pathways. ZT's performance on concrete and abstract words is shown in Table 2. In Arabic **wo**, the percentage of correct responses is 42.59% (23/54) on concrete words and 22.22% (12/54) on abstract words, a difference of 20.37 percentage points in favor of concrete words. In French, the percentage of correct responses is 56.66% (34/60) on concrete words and 26.66% (16/60) on abstract words, a difference of 30 percentage points in favor of concrete words. If we look at Plaut and Shallice's data on lesion location and lesion severity affecting performance on concrete and abstract words (see Table 8), ZT's reading performance on abstract and concrete words corresponds to a lesion severity affecting the O → I connections of 0.25 for Arabic and of 0.20 for French (lesioned O → I connections are indicated by dotted arrows in Fig. 13).

With respect to error distribution, the model predicts more visual than semantic errors on abstract words but more semantic than visual errors on concrete words. In Plaut and Shallice (1993, p. 459) simulations, visual errors are higher for abstract than concrete words; conversely, the proportion of semantic errors is higher for concrete than abstract words. As reported in Fig. 14, ZT's error distribution in Arabic follows Plaut and Shallice's prediction. Although the observed differences are not significant, the patient produced more visual (12/42 = 29%) than semantic

Table 8

Correct performance for concrete and abstract words for each lesion location as a function of lesion severity. Plaut & Shallice (1993) Deep dyslexia: a case study of connectionist neuropsychology. *Cognitive Neuropsychology* 10 (5) p. 457. Reprinted by permission of Psychology Press Ltd., Hove, UK.

Lesion location	Word type	Lesion severity						
		0.05	0.10	0.15	0.20	0.25	0.30	0.40
O → I	Concrete	88.6	75.0	67.1	52.7	44.2	38.3	23.0
	Abstract	69.0	50.8	40.0	25.4	21.3	16.1	10.4
	Difference	19.6	24.2	27.1	27.3	22.9	22.2	12.6
I → S	Concrete	75.1	54.8	38.2	28.2	19.9	14.1	6.3
	Abstract	53.9	26.6	16.4	10.0	6.1	3.0	1.2
	Difference	21.2	28.2	21.8	18.2	13.8	11.1	5.1

errors (8/42 = 19%) on abstract words and more semantic (8/42 = 19%) than visual errors (3/42 = 7%) on concrete words.

However, as illustrated in Fig. 15, ZT showed a tendency to produce in French more semantic (14/44 = 32%) than visual errors (8/44 = 18%) on abstract words ($\chi^2 = 1.51$, $P > 0.05$), as well as more semantic (9/44 = 20%) than visual errors (2/44 = 5%) on concrete words ($\chi^2 = 3.74$, $P = 0.053$).

Given that the stimuli sets in the two languages refer to the same concepts (French concrete and abstract words were translated into Arabic) a difference in error distribution between the two languages cannot be accounted for by a difference in their degree of concreteness. A possible interpretation is that the higher semantic error rate in reading both abstract and concrete words in French results from the lesions affecting the S → Ip connections which, as reported above, are more severe in French than in Arabic. This interpretation is corroborated by the distribution of visual/phonological-then-semantic errors. Examination of the error distribution in Table 3 reveals that ZT produced 11 visual/phonological-then-semantic errors in French but none in Arabic. Moreover, this error type in French was more frequent in reading abstract than concrete words. According to Plaut and Shallice (1993), visual-then-semantic errors result from confusion in the input pathway (O → I) followed by a semantic confusion in the output (S → Ip) network. Given that the reading of abstract words relies more on the direct pathway and that S → Ip connections are more severely lesioned in French than in Arabic, visual/phonological-then-semantic errors are more likely to occur in French than in Arabic, and more likely to occur on abstract than on concrete words.

6.4. Error distribution across tasks

As reported in the previous section, in both languages the semantic error rate was

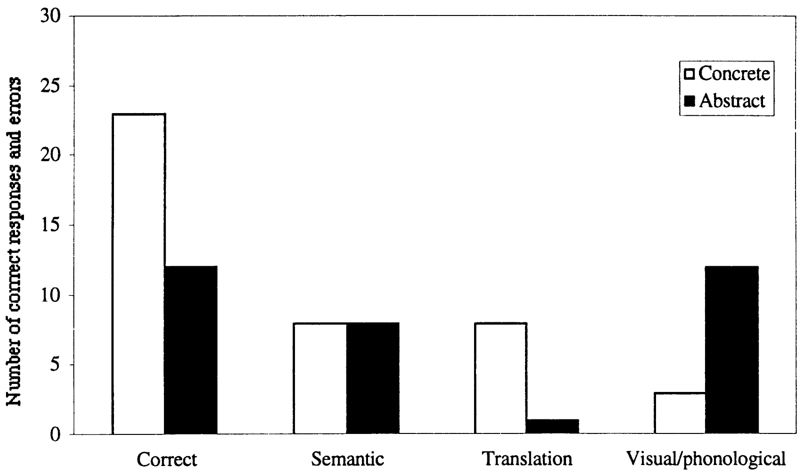

Fig. 14. Number of correct responses and error distribution in reading aloud of concrete and abstract word stimuli in Arabic **wo**. Error types with a number of errors ≥5 in either stimulus type are plotted.

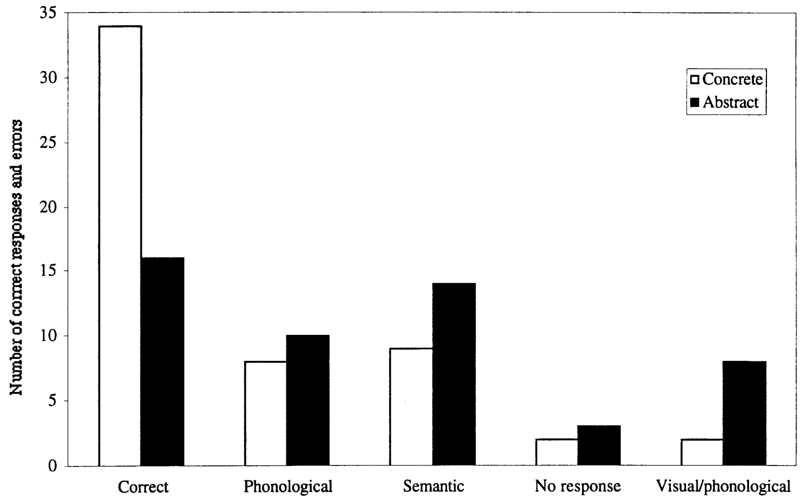

Fig. 15. Number of correct responses and error distribution in reading aloud of concrete and abstract word stimuli in French. Error types with a number of errors ≥5 in either stimulus type are plotted.

higher in oral picture naming (see Table 5; Arabic: 22% = 22/100; French: 28% = 28/100) than in oral reading (see Table 3; Arabic **wo**: 10.16% = 62/610; Arabic **w**: 10.11% = 28/277; French: 15.55% = 86/553). These results may stem from the use of distinctive stimuli in the two tasks. To eliminate this bias, we designed an oral picture naming task and a reading task, which included identical stimuli. We added written picture naming and writing to dictation, two other tasks in which output deep dyslexics are expected to produce semantic errors. In the four tasks, sets of stimuli composed of 55 and 60 items in Arabic and French, respectively, were administered to the patient. The sets were almost identical in that the Arabic set contained 55 of the 60 French items. The percentage of correct responses in Arabic was 51% (28/55), 70% (39/55), 43% (24/55), and 45% (25/55) in oral picture naming, reading aloud, written picture naming, and writing to dictation, respectively. In French, the percentage of correct responses was 65% (39/60), 53% (32/60), 45% (27/60), and 63% (38/60), respectively. More interestingly, despite the variation in the performance across tasks and languages, semantic errors were found in all four tasks both in Arabic and French. Moreover, as indicated in Figs. 16 and 17, the semantic error rate shows an identical rank ordering in both languages (oral picture naming > written picture naming > reading aloud > writing to dictation).

A possible interpretation of these results is that the production of semantic errors depends on the location of the initial activation: the closer the initial activation to the lesioned S → Ip connections, the more likely semantic errors are to occur. Initial activation is located on the semantic layer in oral and written picture naming, resulting in higher semantic error rates. Conversely, in reading and writing to dictation, the initial activation is on the orthographic and the phonological layers respectively, resulting in lower semantic error rates. This interpretation is congruent with

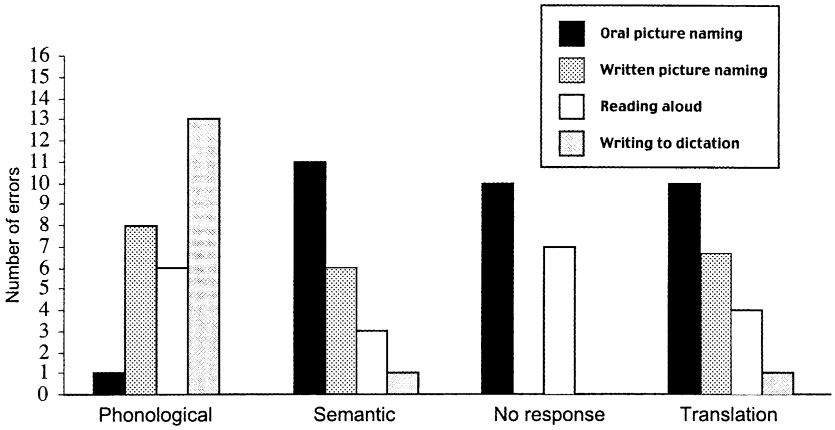

Fig. 16. Error distribution across tasks for the 55 Arabic stimuli. Error types with a number of errors ≥5 in any of the four tasks are plotted.

the principle that early lesions in a cascade are more detrimental than late lesions (Sitton, Mozer, & Farah, 2000).

6.5. Delayed repetition

Results in delayed repetition revealed a trend toward a double dissociation in the two languages: the increased delay resulted in a lower rate of semantic errors in Arabic and a higher rate in French whereas phonological errors increased in Arabic but decreased in French (see Figs. 4 and 5). Lesions affecting S → Ip connections for

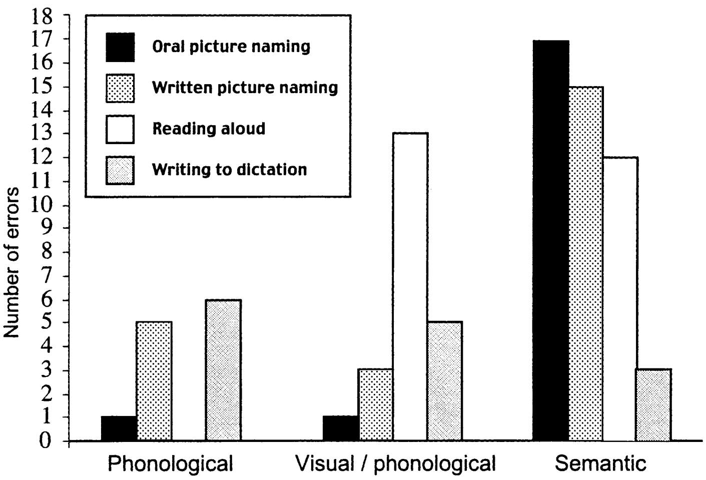

Fig. 17. Error distribution across tasks for the 60 French stimuli. Error types with a number of errors ≥5 in any of the four tasks are plotted.

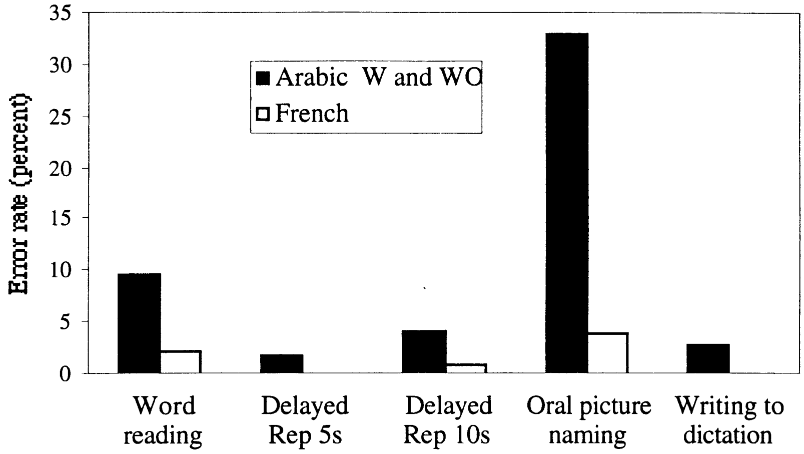

Fig. 18. Distribution of translinguistic errors across tasks in Arabic **w** and **wo**, and in French.

French and Ip → P connections for Arabic were posited earlier to account for the dissociation in the semantic error rate. The difference in the location of the lesioned connections may account for the double dissociation in delayed repetition. In both languages, an increase in the delay taxes the semantic system heavily. The higher semantic error rate in the 10 s delayed repetition in French is a result of lesions to the S → Ip connections whereas in the 10 s delayed repetition in Arabic the higher phonological error rate results from lesions to Ip → P connections.

6.6. Distribution of translinguistic errors

Fig. 18 shows that translinguistic errors are much more frequent in Arabic than in French. We assumed earlier that translation errors occur because the two languages build attractor basins that are connected via the semantics. More specifically, translation errors produced in tasks involving an oral output occur when S → Ip connections are first activated in Arabic, then Ip → P connections are activated in French rather than in Arabic.

Some psycholinguistic models for the bilingual mental lexicon claim that the links between concepts and the lexicon may differ in L1 and L2. According to the Kroll and Stewart (1994) model, the links from concepts to the lexicon are stronger in L1 than in L2. Within a connectionist approach, this would entail stronger and/or more numerous connections between semantics (concepts) and orthography and between semantics and phonology in Arabic, ZT's dominant language. Therefore, if one assumes that the S → Ip connections are stronger and/or more numerous in Arabic than in French, one should expect translation errors to occur more frequently when the patient is tested in Arabic (L1) than in French (L2). Translation errors may therefore be construed as an unconscious adaptive strategy on the part of the patient when experiencing difficulties in activating S → Ip connections in French and Ip → P connections in Arabic.[4]

6.7. Nonword reading in Arabic and in French

The 40–60 network in Plaut and Shallice (1993) does not account for nonword reading since it lacks direct non-semantic orthography-to-phonology connections. Consequently, it cannot account for the phonological priming effect found in the LDT2 task. However, the orthography-to-phonology connections are present in more recent connectionist models (Plaut, 1997; Plaut, Mc Clelland, Seidenberg, & Patterson, 1996), which allow us to account for error pattern differences found across languages in ZT's reading of nonwords.

Nonword reading is slightly better in French (score of 10/84 = 11.90%) than in Arabic (score of 3/63 = 4.74% on nonwords **wo** and of 0/22 = 0% on nonwords **w**), but the difference is not significant. However, error type distribution in the two languages (see Table 4) shows an important discrepancy in the no response rate, which is much higher in Arabic (**wo**: 32/63 = 51%; **w**: 15/22 = 68%) than in French (11/84 = 13%). This no response rate in nonword reading is, in fact, significantly higher in Arabic (**wo**: $\chi^2 = 22.93$, $P < 0.001$; **w**: $\chi^2 = 25.68$, $P < 0.001$) than in French. The structure of the Arabic language may account for the observed discrepancy. A former study conducted with the same patient (Prunet et al., 2000) revealed that the error corpus contained a large number ($n = 119$) of metathesis errors consisting of root consonant reversals (e.g. قرد [qird] 'monkey' → قدر [qidr] 'cooking pot') in Arabic word stimuli. This type of metathesis error was not, however, observed in French. An exhaustive linguistic analysis of metathesis in slips of the tongue, language games and aphasic errors reported in Arabic and other Semitic languages led the authors to claim that the Arabic consonantal root constitutes a privileged unit of access to the mental Arabic lexicon.

In light of this, the higher no response rate in Arabic nonwords may be explained by the fact that the nonwords used in our experiments did not contain an existing consonantal root. Results of the cross-linguistic priming experiment are consistent with this interpretation. A significant priming effect was found when a French nonword (e.g. "*calbée*" [kalbe]) was followed by a homophonous Arabic word كلب [kalbe]). If one assumes that phonological priming involves the mapping of the consonants /k-l-b/ making up the French nonword with the consonantal root in Arabic /k-l-b/, then when an Arabic nonword شاز [ʃɛz] homophonous to the French target word *chaise* was used as a prime, even if root extraction may have occurred, priming could not be obtained since the root does not constitute a lexical unit in French.

[4] One of the reviewers suggested that translation errors could be produced by normal bilingual subjects as well. In fact, ZT's behavior is quite similar to what has been reported on bilingual speakers in code-switching situations.

7. Concluding remarks

Within the three-route model of reading used in the initial stage of this study, bilingual output deep dyslexia is interpreted as resulting from a number of distinct functional lesions disrupting the non-lexical route, the semantic lexical route and the lexical route. Even though this model provides an account for the patient's deficits in each language taken separately, it does not offer a comprehensive theory for bilingual output deep dyslexia. When attempting to account for the dissociation across languages in the distribution of errors, the model leads us to a paradox: a lesion must be posited on the pathway from the semantic system to the French phonological lexicon to account for the higher semantic error rate in French, but the presence of this lesion is incompatible with the higher translation error rate in Arabic. Furthermore, the linear and modular aspects of the model preclude an interpretation of visual errors in the processing of concrete vs. abstract words. Indeed, in such a model, on-line processing is influenced by the features of the words that are represented at each level. Visual errors are presumed to stem from an impairment in visual analysis, a process that is influenced only by the visual properties of the stimuli and not by their semantic features. Given that the concreteness feature is represented in the semantic system, it should not have any influence on the visual error rate.

In contrast to the three-route model, which is limited in its predictive power, the proposed bilingual connectionist network allows us to make predictions with respect to error distribution in the two languages of bilingual deep dyslexic patients.

A first prediction refers to the language dominance. In the extensions to the network that we have proposed, semantics must be common to both languages in order to account for semantic-then-translation and visual/phonological-then-translation errors. To explain both error types, semantics must constitute the bridge towards the second language, an observation that is consistent with models of the bilingual lexicon, which claim a common semantic system. The higher proportion of translation errors in Arabic testing as opposed to French testing was construed as an adaptive strategy by the patient when experiencing difficulties in activating $S \rightarrow Ip$ connections in French and $Ip \rightarrow P$ connections in Arabic. According to the Kroll and Stewart (1994) model, the links between the concepts and the lexicon are stronger in L1 than in L2. We posited that $S \rightarrow Ip$ connections were more severely lesioned in French (L2) than in Arabic (L1). Within the P & S model, this may be due to the fact that these connections were either more numerous or stronger in Arabic (L1) than in French (L2) premorbidly. Therefore, we predict that output deep dyslexic patients showing deep dyslexia in both languages with a similar degree of severity are more likely to produce translation errors when tested in L1 than when tested in L2.

A second prediction issuing from the accommodations proposed for bilingual patients is that the form of translinguistic errors should vary according to the languages spoken by the bilingual patients. Arabic and French have absolutely no resemblance in their orthography, so the occurrence of errors triggered by visual similarity between the words in the two languages is precluded. In bilingual deep dyslexic patients speaking languages written with the same orthographic script (e.g. French, English, Spanish), one should expect the same types of errors found in ZT's performance as well as translinguistic errors triggered by visual and phonological similarity between the two orthographies. For example, one may expect the French word *an* 'year' to be confused with the English article "an" or the French word *botte* [bɔt] 'boot' to be mixed up with the English word [bʌt] 'but'.

To conclude, in this case study the superiority of the connectionist approach over the multi-impairment approach is demonstrated, first through the capacity of the computational properties of the network to account for the co-occurrence of visual/ phonological, semantic, visual and semantic errors, and second in the capacity of the model in predicting error patterns in bilingual deep dyslexia. The presence of cross-language phonological priming obtained in the LDT2 is an indication that activation of the phonology in the other language may occur without semantic activation. Therefore, the semantic layer may not be the only bridge for connections between the two languages of a bilingual subject.

Acknowledgements

This research was supported by the Fonds de la Recherche en Santé du Québec (Grant # 952342) and by the Conseil de la Recherche en Sciences Humaines du Canada (Grant # 410-92-0015). We are grateful to ZT for his cheerful and unconditional participation. Our thanks go to ZT's family for their support, to Suzanne Danault, Speech Therapist and Diane Martineau, Neuropsychologist for their assistance in various aspects of this study, and to Isabelle Peretz, Sylvie Belleville, Martin Arguin, and Daniel Fiset, and the anonymous reviewers for suggestions and useful comments on an earlier version of this paper. Special thanks to Ali Idrissi, Geneviève Duchesne, and Soumeya Sadou for their help in the testing in Arabic and in French and to Benoît Gagnon for designing various figures.

Appendix A. Error type definitions

No response: after a reasonable delay, the patient produced no response.

Circumlocution: the patient produced a sentence to describe the word or the picture stimulus;

e.g.

Arabic: to the stimulus حياة 'life' presented in reading aloud, the patient's response was مرأة و رجل 'woman, man'.

French: to the stimulus *état* 'state' presented in reading aloud, the patient's response was *malade par exemple pour une semaine* 'sick for instance for a week'.

Gestural: the patient used hand or finger gestures to describe the shape of an object or to mimic the action corresponding to a word or picture stimulus;

e.g.

Arabic: to the stimulus سلة 'basket' in reading aloud, the patient produced a hand gesture corresponding to the shape of a basket.

French: to the stimulus *serpent* 'snake' in reading aloud, the patient produced a hand gesture showing a moving snake.

Morphological: the patient's response was morphologically related to the stimulus when corresponding to an inflected or derived form of the stimulus. Morphological errors are by definition semantically related to the stimulus. Note that in French, but not in Arabic, morphologically related words are not mandatorily visually and phonologically related (e.g. *bouche* 'mouth' vs. *buccal* 'oral');

e.g.

Arabic: the patient's response to the noun حماقة 'stupidity' in reading aloud was the derived form أحمق 'stupid'. The patient's response to بارد 'cold' in reading aloud was the feminine form of the derived verb: برد ت 'she is cold'.

French: the patient's response to the verb *goûter* 'to taste' in reading aloud was the derived form *goût* 'taste'. The patient's response to *laisser* 'to let' in reading aloud was an inflected form of the same verb, *laissa* 'he let' past tense.

Morphological-then-translation: the patient's response was a translation (in Arabic in the French testing and in French in the Arabic testing) of a word that is morphologically related to the stimulus. Note that the morphological part of the error does not necessarily precede the translation part. Since there exists no way to distinguish "morphological-then-translation" from "translation-then-morphological" errors, any error not given in the language of testing and not agreeing in gender, number, tense or grammatical class with the stimulus was categorized as a morphological-then-translation error;

e.g.

Arabic: to the stimulus خجل 'shyness' in reading aloud, the patient's response was *timide* 'shy'.

French: to the stimulus *enfant* 'child' in reading aloud, the patient's response was أطفال 'children'.

Other: the patient's response is a word in the language of testing which has no semantic, morphological, visual or phonological relationship with the stimulus;

e.g.

Arabic: in reading aloud, the patient's response to the stimulus رمز 'symbol' was صوت 'voice'.

French: in reading aloud, the patient's response to the stimulus *vanité* 'vanity' was *poignée* 'handle'.

Perseveration: the patient repeated a response produced earlier in the testing session;

e.g.

Arabic: no perseveration errors were found in Arabic.

French: in the 5 s delayed repetition, the patient's response to the stimulus *théière* 'tea pot' was *désir* 'desire', a stimulus given earlier in the testing.

Phonological: the patient's response was a *nonword* sharing phonological and/or visual similarity with the stimulus;

e.g.

Arabic: in reading aloud, the patient's response to the word متجر 'shop' was the nonword [manzar].

French: in reading aloud, the patient's response to the word *banalité* [banalite] 'banality' was the nonword [bananli].

Phonological/lexical: the patient's response in repetition was a *word* sharing phonological and/or visual similarity with the stimulus;

e.g.

Arabic: in delayed repetition, the patient's response to the word لفظ 'term' was the word نفط 'gas'. French: in delayed repetition, the patient's response to the word *assister* [asiste] 'to attend' was the word *assis* [asi] 'seated'.

Semantic: the patient's response was a word semantically but not morphologically and thus, not visually and/or phonologically related to the stimulus;

e.g.

Arabic: in reading aloud, the patient's response to the stimulus ورد 'roses' was زهر 'flowers'.

French: in reading aloud, the patient's response to the stimulus *gain* 'earning' was *argent* 'money'.

Semantic-and-phonological: the patient's response was a *nonword* sharing phonological and/or visual similarity with a word semantically related to the stimulus;

e.g.

Arabic: in written picture naming the patient's response to the stimulus جريدة 'newspaper' was الاجبار, a nonword orthographically related to الأخبار 'news', which is semantically related to the stimulus.

French: in oral picture naming the patient's response to the stimulus *thermomètre* 'thermometer' was [sãperatʏr], a nonword phonologically related to *température* 'temperature', which is semantically related to the stimulus.

Semantic-then-translation: the patient's response was a translation (in Arabic in the French testing and in French in the Arabic testing) of a word that is semantically related to the stimulus. Note that the semantic part of the error does not necessarily precede the translation part. Since there exists no way to distinguish "semantic-then-translation" from "translation-then-semantic" errors, any error not given in the language of testing and semantically related to the stimulus was categorized as a semantic-then-translation error;

e.g.

Arabic: in reading aloud, the patient's response to the word قانون 'law' was *juge* 'judge'.

French: in reading aloud, the patient's response to the word *éponge* 'sponge' was بحر 'sea'.

Translation: the patient's response was a translation of the stimulus in Arabic into French testing and a translation into French in Arabic testing;

e.g.

Arabic: the patient's response to the stimulus الخميس 'Thursday' was *jeudi* 'Thursday'.

French: the patient's response to the stimulus *poisson* 'fish' was سمكة 'fish'.

Visual/phonological: the patient's response was a word visually and/or phonologically but neither semantically nor morphologically related to the stimulus. At least 50% of the letters (phonemes) of the response were the same and in the same order as in the stimulus word;

e.g.

Arabic: in reading aloud, the patient's response to the stimulus كره 'to hate' was كرة 'ball'.

French: in reading aloud, the patient's response to the stimulus *concept* 'concept' was *correct* 'correct'.

Visual/phonological (root): the patient's response was a word visually and phonologically but not semantically related to the stimulus, which contained the same Arabic root;

e.g.

Arabic: in reading aloud, the patient's response to the stimulus ملئ 'to fill up' was إملاء 'dictation'.

Visual/phonological-and-semantic: the patient's response was a word visually and/or phonologically and semantically related to the stimulus;

e.g.

Arabic: no visual/phonological and semantic errors were found in Arabic.

French: in reading aloud, the patient's response to the stimulus *hangar* 'shed' was *grange* 'barn'.

Visual/phonological-then-morphological: the patient's response was a word that is morphologically related to a bridge word, which is in turn visually and/or phonologically related to the stimulus;

e.g.

Arabic: no visual/phonological-then-morphological errors were found in Arabic.

French: in reading aloud, the patient's response to the stimulus *bocal* 'jar' was *bouche* 'mouth', a word morphologically related to *buccal* 'oral', which in turn is visually and phonologically close to the stimulus *bocal*.

Visual/phonological-then-semantic: the patient's response was a word that is semantically related to a bridge word, which is in turn visually and/or phonologically related to the stimulus;

e.g.

Arabic: in reading aloud, the patient's response to the stimulus أسقف 'preacher' was سطح 'roof', a word semantically related to the bridge word سقف 'ceiling', which is in turn visually and phonologically similar to أسقف.

French: in reading aloud, the patient's response to the stimulus *lingot* 'ingot' was *chemise* 'shirt', a word semantically related to the bridge word *linge* 'cloth', which is in turn visually and phonologically similar to *lingot*.

Visual/phonological-then-translation: the patient produced a translation (into French in the Arabic testing and into Arabic in the French testing) of a bridge word, which is visually and/or phonologically close to the stimulus;

e.g.

Arabic: in reading aloud, the patient's response to the stimulus شوكة 'fork' was *chocolat* 'chocolate' through the Arabic bridge word شوكولا 'chocolate', a word visually and phonologically close to the stimulus شوكة 'fork'.

French: in reading aloud, the patient's response to the stimulus *portillon* 'gate' was فراشة 'butterfly' through the French bridge word *papillon* 'butterfly', a word visually and phonologically close to the stimulus *portillon* 'gate'.

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