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Competition between past and present
Assessment and interpretation of verbal perseverations

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Summary
Perseveration consists of the inappropriate repetition of a preceding behaviour when a new adapted response is expected. We have developed statistical tools that make it possible to reveal such perseverations, assess their significance and study their finer characteristics, such as their temporal course and impaired processing level. This approach is illustrated and evaluated through analyses of naming errors produced by three patients with impairments affecting different stages of the processing chain leading from visual perception to speech production. These examples of perseverations include the intrusion not only of whole words (patient R.A.V.) but also of isolated phonemes (patient D.U.M.) or of visual features (patient Y.M.) from previous trials. In all cases, the probability that an error is a perseveration from a previous trial is an exponentially decreasing function of the lag between the two trials considered. This suggests that perseverations reflect a decaying internal variable, such as an internal level of activation of previous utterances. Based on these empirical results, we put forward a tentative mechanism for the generation of perseverations: whenever a given processing level is deprived of its normal input, persistent activity inherited from previous trials is no longer overcome by current input, and is revealed in the form of perseverations.

Keywords: language; perseveration; aphasia; speech; neuropsychology

Abbreviations: LVF = left visual field; PP = perseveration probability; RVF = right visual field

Introduction
Perseveration has long been recognized as a frequent consequence of brain damage (for historical references see Hudson, 1968). It consists of the inappropriate repetition of a preceding behaviour when a new adapted response is expected. Sandson and Albert (1984) distinguished three main types of perseveration, distinguished by the level of complexity of the behaviour that is affected. At the highest level, 'stuck-in-set' perseveration reflects behavioural rigidity, an inability to switch from one task or response strategy to another. Such an impairment may be revealed with the Wisconsin Card Sorting Test, and generally results from prefrontal cerebral lesions (Milner, 1963; Dehaene and Changeux, 1991). At the lowest level, 'continuous' perseveration consists of the compulsive iteration of elementary motor patterns, such as irrepressibly drawing series of loops instead of a simple circle (Luria, 1965). Finally, at an intermediate level of complexity, so-called 'recurrent' perseveration consists of the repetition of a previously emitted response when processing a series of consecutive stimuli. A typical example of recurrent perseveration is the production of the same word on successive trials of an object-naming task, as has been reported in some aphasic patients (e.g. Buckingham *et al*., 1978; Albert and Sandson, 1986; Papagno and Basso, 1996) and in patients with optic aphasia or visual agnosia (Lhermitte and Beauvois, 1973; Iorio et al., 1992). Verbal perseveration should be clearly distinguished from the stereotyped behaviour of aphasic patients whose possible utterances are limited to a few phonemes, words or automatic expressions. While stereotypes correspond to a global and permanent bias for producing a small and fixed set of utterances, perseverations are local in time and consist of the unexpected intrusion of previous utterances in the current speech output.

Although their existence is well acknowledged, perseverative phenomena mostly become obvious on clinical testing. They are frequently described qualitatively rather than quantitatively, and their significance is rarely assessed statistically. Consequently, perseverations have not been subjected to thorough cognitive neuropsychological analysis. Their time-course, the conditions of their appearance and their underlying mechanism have not been elucidated. The present study attempts to fill this gap. We developed original methods to analyse verbal perseverations in corpora of patients' utterances. These methods enabled us (i) to reveal such perseverations even when they are not perceptible on simple inspection of the data, (ii) to test their statistical significance, and (iii) to study their finer characteristics, such as temporal course, dependence on stimulus or response characteristics, impaired processing level, etc. This approach, which may in principle apply to a wide variety of perseverative phenomena, is illustrated and evaluated in this study through analyses of naming errors produced by three patients with impairments affecting different stages of the processing chain leading from visual perception to speech production. These examples of perseveration include not only the intrusion of previously emitted words (lexical perseverations), but also the contamination of current speech output by phonological, visual or semantic features of previously emitted words.

In the final section, capitalizing on our analysis of their fine characteristics, we put forward a general theoretical account of recurrent verbal perseveration in the framework of current models of speech production. We suggest that a single mechanism, occurring at different stages of speech production, may explain not only lexical but also other types of verbal perseverations.

Principles of perseveration analysis: the case of patient Y.M.

In this section we describe the statistical methods that we have used to analyse perseverative phenomena. The algorithms are best described using a relatively simple example, the case of a patient who produced frequent errors and perseverations when reading arabic numerals aloud.

Case history

Patient Y.M. was a 58-year-old man who, following left temporal lobectomy for a malignant tumour, made numerous errors (21.8%) when reading arabic numerals aloud. Most errors (86.6%) consisted of digit substitutions (e.g. 916 → 416). In a detailed study, Cohen and Dehaene (1991) and Dehaene and Cohen (1995) showed that Y.M.'s number-reading errors resulted from impaired visual identification of arabic numerals, leading to incorrect structural representation of the input, or visual number form. The visual number form is a numerical equivalent of the visual word form involved in word recognition (Warrington and Shallice, 1980). It represents the identity and relative position of the perceived digits and, in the left hemisphere, it serves as the input to the visual-to-verbal translation process. One of the most striking features of Y.M.'s behaviour was the occurrence of perseverations in about one-third of his errors. For instance, in the following example Y.M. produced an extended series of inappropriate 7s:

Stimulus	Response
78	78
233	**7**33
6534	**7**534
52	**7**3
6453	**7**453

However, most cases of perseveration were not as obvious, as illustrated in this second example:

Stimulus	Response
122	1**8**2
818	818
8	8
2341	2341
6241	62**8**1

In this example Y.M. produced two inappropriate 8s. The difficulty is to decide objectively whether this set of productions contains actual perseverations, or whether the output 8 was selected by the patient at random or under the influence of some permanent preference for the digit 8.

Lag distribution analysis

One way to answer this question is to look at the series of responses and try to relate each error to a preceding response. For each error, we look backwards in time until we reach a response that matches the error considered. We then noted the number of trials (or 'lag') separating the two responses. Consider, for instance, the erroneous 8 in 6281 in the above example. We find that the patient had produced an 8 two trials earlier (lag = 2). We may then plot the frequency distribution of these lags, computed over all errors. A large proportion of matches at small lags suggests the occurrence of perseverations.

Of course, there is some probability that, by chance alone, an error matches a relatively recent response. Hence, the observed distribution of lags should be evaluated against chance level. This can be done by comparing the observed lag distribution with the distribution obtained by the same process after the sequence of trials has been shuffled randomly. Shuffling preserves the number and nature of errors, while destroying their local serial organization. Thus, any local series of responses should appear as an excess of matches at small lags in the observed distribution, relative to the random distribution. Note that any global bias in producing responses, such as a patient producing an 8 as a stereotyped response throughout the testing session, would contribute equally to the observed and random distributions, and would therefore not be confounded with local perseverations. In all the following analyses, we shuffled data sets randomly 30 times, ran the perseveration analysis on each shuffled set, and used the averages of the resulting values as reliable estimates of chance level. Note that when the data consisted of several distinct experimental lists the scrambling was performed within each list. This is a

Table 1 *Lag distribution analysis of patient Y.M.'s number-reading errors*

Lag	Observed distribution		Random distribution			
			Global analysis		Time-corrected analysis	
	No. of matches	Remaining non-matched errors	No. of matches	Remaining non-matched errors	Time-corrected no. of matches	Remaining non-matched errors
1	202	131	89.5	243.5	89.5	243.5
2	50	81	65.7	177.8	35.3	95.6
3	35	46	44.7	133.1	20.4	60.6
4	14	32	33.3	99.8	11.5	34.5
5	10	22	24.4	75.4	7.8	24.2
6	7	15	18.6	56.8	5.4	16.6
7	2	13	13.2	43.6	3.5	11.5
8	4	9	10.3	33.3	3.1	9.9
9	1	8	7.6	25.7	2.1	6.9
10	2	6	5.7	20	1.8	6.2
11	1	5	3.7	16.3	1.1	4.9
12	1	4	3.6	12.7	1.1	3.9
13	2	2	2.2	10.5	0.7	3.3
14	0	2	2.1	8.4	0.4	1.6
15	0	2	1.2	7.2	0.3	1.7
Unmatched errors	2		7.2		148.9	
Total	333		333		333	

conservative procedure in that it does not treat stereotypes (i.e. permanent biases) restricted to one list as genuine local perseverations. (NB Comparing the observed lag distribution with that expected under random shuffling of the original experimental lists is appropriate only if there are no sequential dependencies in the original lists. Otherwise, random shuffling may systematically under- or overestimate the probability of observing repeated responses under the null hypothesis. Thus, a consequential methodological point is that data should be collected from patients using lists of randomly ordered trials. This was the case in all the experiments reported here.)

We applied this lag distribution analysis to the corpus of Y.M.'s 1858 reading trials, including 305 errors. Each erroneous digit ($n = 333$), i.e. each digit that was part of a response but not of the corresponding stimulus, was matched against the digits produced on preceding trials. Table 1 shows the resulting actual (columns 2 and 3) and random (columns 4 and 5) lag distributions. As seen in Fig. 1A, perseverations appeared as an excess of small lags compared with chance level. The two distributions could then be compared using χ^2 tests for goodness of fit. They were found to differ significantly [$\chi^2(10) = 201.6$, $P < 0.001$], indicating that there were local regularities in the temporal organization of errors. [Note that the random distribution is itself a decreasing function of time. Assuming that a given error has a constant probability P of occurring on any trial (in the absence of perseveration), the probability that the closest match of an error will be found in L trials earlier is $(1 - P)^{L-1} P$.]

The observed difference could still be due to a subtle change in the shape of the lag distribution. We can, however, design additional statistical tests of the specific hypothesis that small lags are over-represented in the actual data. Consider first the number of matches at lag 1 (Table 1). Out of a total of 333 errors, 202 (60.7%) were matched at lag 1, while chance alone predicted only a mean of 89.5 matches (26.9%). The significance of this excess can again be tested by a χ^2 test for goodness of fit, here giving $\chi^2(1) = 59.0$, $P < 0.001$. This process can be continued at further lags. Out of 131 errors that could not be matched at lag 1, 50 (38.2%) were matched at lag 2. However, this figure cannot be directly compared with the raw figure of 65.7 given by the random distribution for lag 2. This is because the test at lag 2 should take into account the number of errors that were actually matched at lag 1. The value of 65.7 should thus be corrected by taking into account the actual number of remaining errors after lag 1 (131) rather than its random value (243.5). The number of observed matches at lag 2, i.e. 50, must therefore be compared with a predicted value of $65.7 \times 131 \div 243.5 = 35.3$. Again, this difference is significant [$\chi^2(1) = 9.56$, $P = 0.002$]. Applying the same procedure, we found a significant effect at lag 3 [$\chi^2(1) = 14.0$, $P < 0.001$], and no significant effect beyond that point. The time-corrected values of the random lag distribution are shown in columns 6 and 7 of Table 1. Figure 1B illustrates the observed and predicted values for the number of matches at each lag. An excess of errors is clearly perceptible at lags 1, 2 and 3. In other words, digits produced on trial T tend to be produced again on subsequent trials $T + 1$, $T + 2$ or $T + 3$. This provided a first quantitative estimate of the latency of perseverations in patient Y.M.

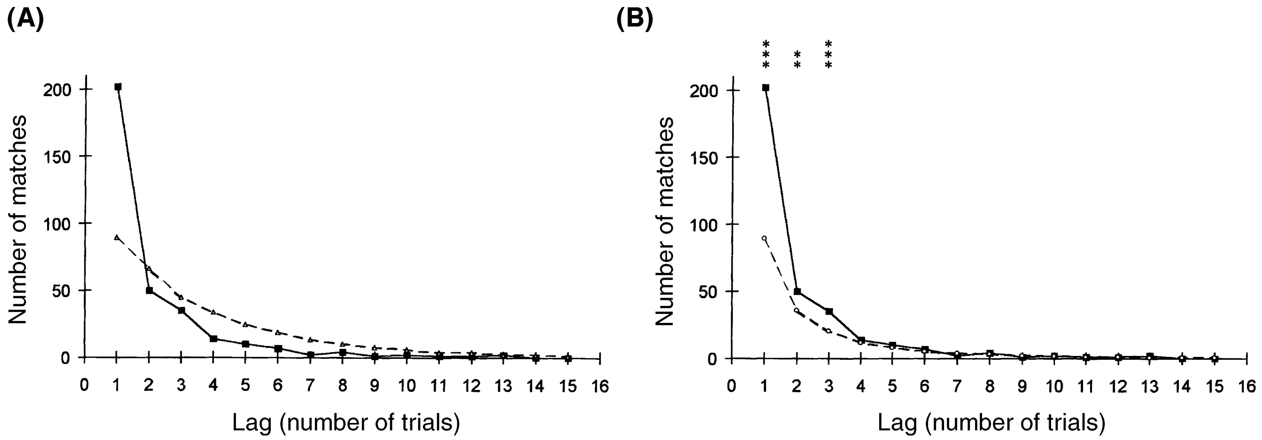

Fig. 1 Lag distribution analysis of patient Y.M.'s number-reading errors. At each lag the observed number of matches (closed squares, solid line) is compared with the chance level (dashed line). (**A**) Chance level (open triangles) is computed by performing the analysis after scrambling the original data. (**B**) Chance level (open circles) corrected to take into account actual matches at shorter lags. This allows statistical comparison, at each lag, of the observed and random distributions. $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

Perseveration probability analysis

While the lag distribution analysis is able to reveal local perseverations and to measure their duration, it does not capture all the meaningful temporal aspects of this phenomenon. For instance, it is sometimes the case that a stimulus is read correctly on trial *T*, and that the response then recurs erroneously on several consecutive trials $T + 1$, $T + 2$, $T + 3$, etc. (see example above). Since the lag distribution analysis takes into account only the first match of each error with a previous trial, it is not sensitive to such perseverative series. The method merely treats such series of perseverations as multiple independent perseverations at a lag of 1. A different method is needed to link each error to all preceding trials, including the first (possibly correctly read) trial of the series.

We therefore designed a second method of analysis which took into account multiple matches of each error with previous trials. For each error, we again looked backwards in time as far as to some arbitrary lag (here 15), and at each lag we examined whether the response matched the error under consideration. The only difference from lag distribution analysis was that we did not stop at the first match. We therefore obtained, for each lag *L*, the number of matches $M(L)$ and the number of non-matches $N(L)$ at this lag. The ratio

$$\frac{M(L)}{N(L) + M(L)},$$

which we term the 'perseveration probability', or $PP(L)$, is the final outcome of this analysis. This ratio can be interpreted as follows: if the patient produces an error on trial *T*, $PP(L)$ provides an estimate of the probability that this error matches the response produced on trial $T - L$. For instance, there was a 41.4% perseveration probability at lag 2. This means that if the patient made an error on a given trial, there was a 41.4% probability that the erroneous digit had been produced on trial $T - 2$, whether or not $T - 2$ was the closest match. Again, the level of the perseveration probability under the null hypothesis that there are no perseverations can be computed by running the same analysis after shuffling the trials randomly.

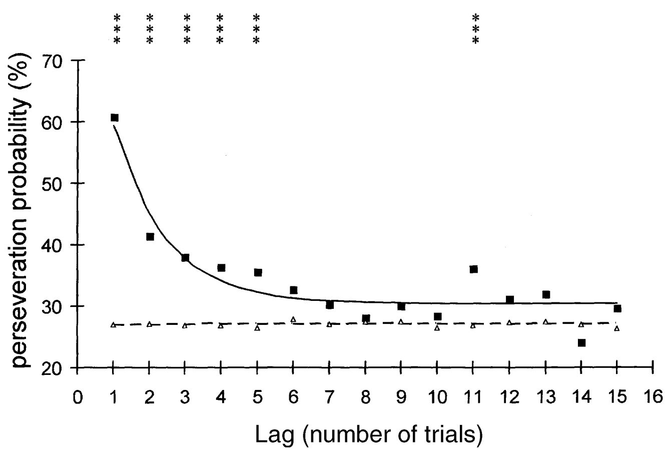

Fig. 2 Perseveration probability analysis of patient Y.M.'s number-reading errors. At each lag the observed perseveration probability (closed squares) is compared with chance level (open triangles). Solid and dashed lines are exponential curves fitted to the observed and chance values, respectively. $^{***}P < 0.001$.

Figure 2 shows the resulting curves when this analysis was applied to patient Y.M.'s number-reading errors. While perseveration probability should have been a constant according to the null hypothesis, the observed values were much higher at small lags and smoothly decreased down to an asymptotic level, which was reached at about lag 6. The temporal duration of the phenomenon was estimated by comparing the actual and the random probabilities at each lag using the χ^2 test. In the present case, the two curves differed significantly at lags 1–5 ($P < 0.001$). Small but significant effects were also observed at lag 11, although it should be noted that no correction for multiple statistical tests was applied. Note that its sensitivity to multiple matches explains why the perseveration probability analysis showed significant perseverations up to lag 5, while the lag distribution analysis was significant only up to lag 3. Take, for instance, the sequence 78, 733, 7534, 73, 7453 produced by patient Y.M. For each erroneous 7, the present analysis took into account not only the match with the immediately preceding trial but also the matches with all preceding 7s in the series. For the last digit 7 produced in this series, the perseveration probability analysis detected matches at lags 1–4, while the lag distribution analysis would simply reject matches beyond lag 1.

The observed perseveration probability curve is well fitted by a decreasing exponential of the form $PP(L) = \alpha + \beta \times 2^{-L/\tau}$, where α is the asymptotic value of *PP*, β is the amplitude of the perseveration effect and τ is the characteristic time of perseverations (half-life), expressed as the number of trials. In the present case, a non-linear regression analysis yielded the following parameter values: $\alpha = 30.3$, $\beta = 57.2$ and $\tau = 1.02$. This model, which accounted for $r^2 = 88.3\%$ of the variance, indicates that approximately with each elapsed trial (τ being close to 1), the rate of perseverations exceeding chance level is halved. Note that the asymptote of 30.3% remained slightly above chance level (27.0%). It remains to be assessed whether this small effect reveals the existence of a long-term component in perseverative phenomena, although the significance at lag 11 suggests that such is the case. The bulk of perseverations, however, decreased rapidly across trials.

The interpretations of the lag distribution and of the perseveration probability analyses should be carefully distinguished. For instance, in the present case a significant effect at lag 3 in the lag distribution analysis is a straightforward indication that a digit produced on a given trial covertly remains a privileged candidate for response on the following three trials. This effect shows that the mechanism underlying perseverations actually has a duration of at least three trials. In contrast, while lag distribution analysis allows the quantification of the striking phenomenon of perseveration series, a significant effect at lag 5 does not necessarily mean that the underlying activation of perseverated words has a duration of five trials. Thus, a perseveration at lag 2 may itself give rise to a subsequent perseveration at lag 3, resulting in an apparent perseveration at lag 5 relative to the initial utterance in the series, even if the internal phenomenon causing perseveration has an actual duration of only three trials.

Variants of the perseveration analyses

We have presented the two methods of perseveration analysis through the concrete example of digit perseverations in patient Y.M. For the sake of simplicity, however, we made several implicit assumptions concerning the underlying properties of these perseverations. Here, we show how variants of the methods can be used to test these hidden assumptions explicitly.

The influence of stimuli versus responses

The principle behind our methods is to try to match each error with previous trials. In the above analyses, this matching procedure was applied only to the patient's previous responses. An alternative possibility, however, would be to try to match errors with previous stimuli. From a purely methodological point of view, these two possibilities seem equally valid. One should assess, however, which is the more appropriate and sensitive for detecting perseverations.

Of course, since the patient's error rate was low, most of the digits in the response were actually correct and therefore present both in the stimulus and in the response. Thus, directly applying the methods either to the stream of stimuli or to the stream of responses would yield very similar results. In order to separate stimulus and response determinants of perseverations, one should estimate separately the perseverations induced by correctly produced stimuli, stimuli that are not responded to properly, and responses that do not correspond to an actual stimulus. In the case of patient Y.M., one must assess separately the influence of three categories of digits: (i) those present in the stimulus but not in the response (S+R–); (ii) those present in both the stimulus and the response (S+R+); and (iii) those present only in the response (S–R+). For instance, when Y.M. read aloud 6241 as 3841, the S+R– digits were 6 and 2, the S+R+ digits were 4 and 1, and the S–R+ digits were 3 and 8. It was then possible to perform our analyses three times, by trying to match errors against each of these three types of digits in the preceding trials.

This procedure was applied to Y.M.'s number-reading corpus. The three corresponding sets of diagrams are shown in Fig. 3. Digits present in the response, whether they were correct (S+R+) or incorrect (S–R+), were at the origin of significant perseverations. In contrast, S+R– digits, i.e. stimulus digits that were not part of the patient's utterances, had no influence whatsoever. Of course, the perseveration curves were much more stable for S+R+ digits than for S–R+ or S+R– digits because the latter were much less numerous. Still, the evidence indicates that a digit can enter into a perseveration on subsequent trials only inasmuch as it has been actually uttered in the patient's response, either correctly or as an error. In the following we present only analyses based on response-matching. The bulk of the evidence, in our work, indicates that if some feature of a stimulus has not made its way into the patient's response it does not contribute to subsequent perseverations.

Words or digits?

Another implicit assumption in the above analyses is that Y.M.'s errors should be construed as *digit* substitutions. Alternatively, those errors could be interpreted as *word*

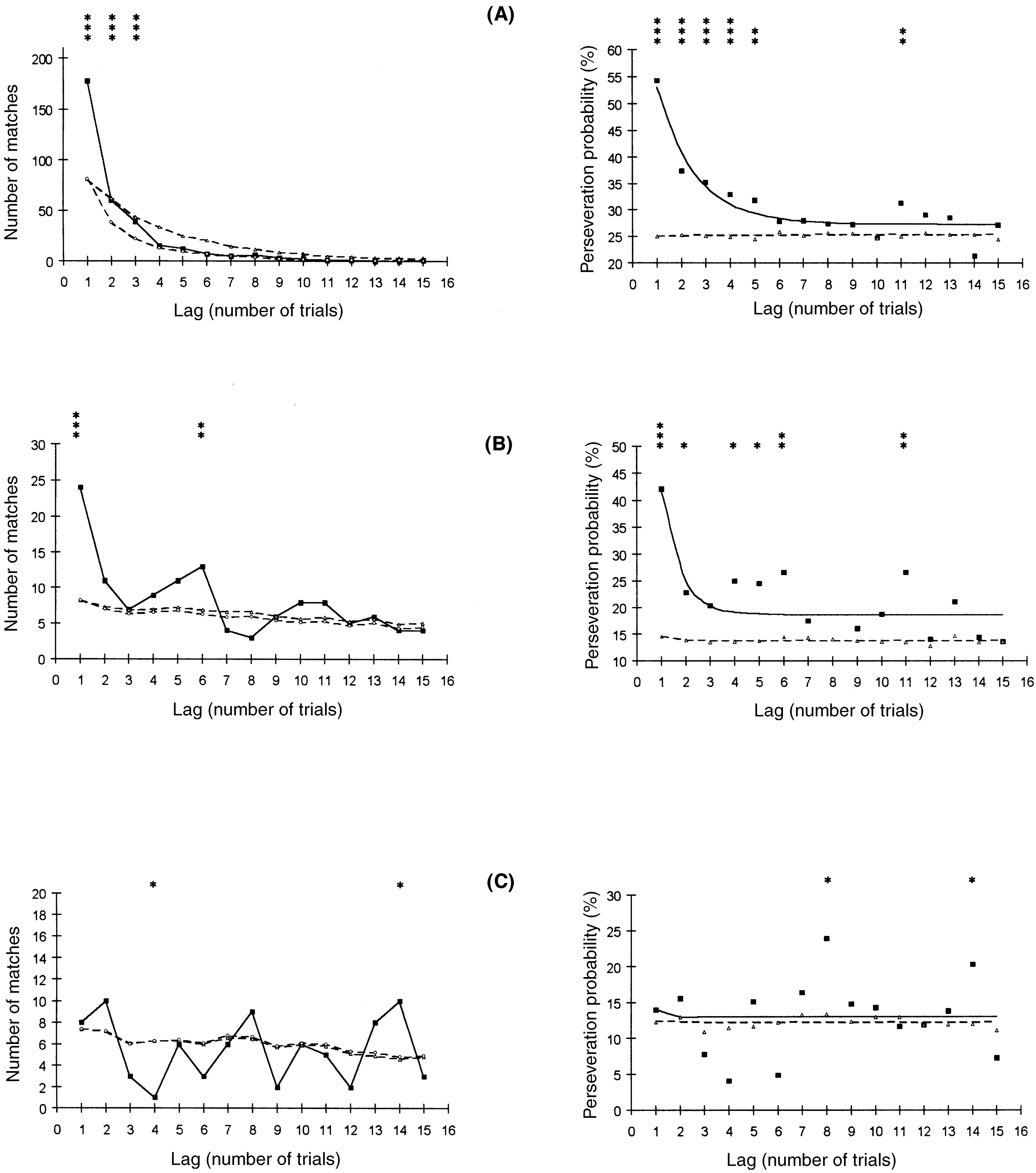

Fig. 3 Lag distribution and perseveration probability analyses of patient Y.M.'s number-reading errors, performed by matching errors (**A**) with previous digits present in both the stimulus and the response, (**B**) with previous digits present only in the response, and (**C**) with previous digits present only in the stimulus. Graphic conventions: see Figs 1 and 2.

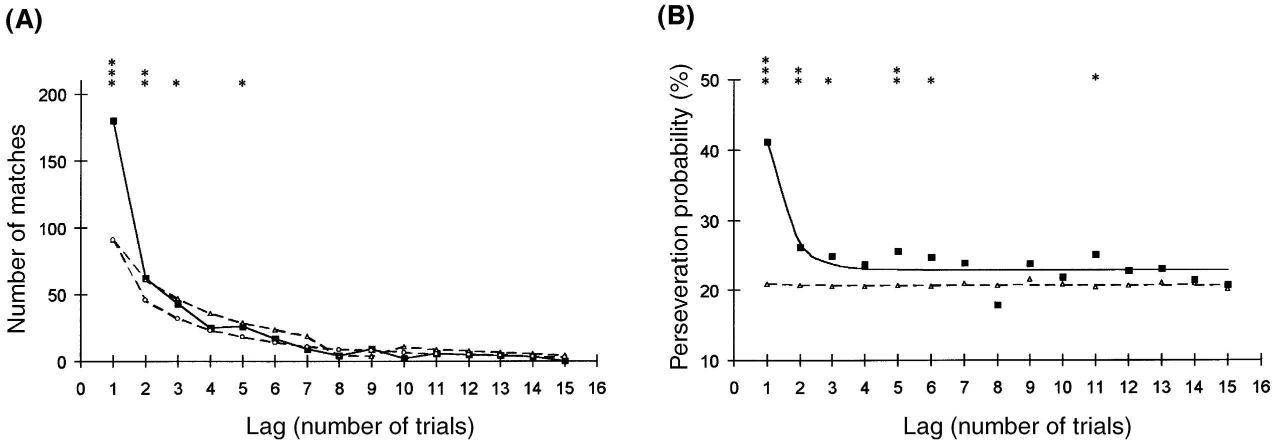

Fig. 4 Lag distribution and perseveration probability analyses of patient Y.M.'s number-reading errors, performed after coding targets and responses in word format. Graphic conventions: see Figs 1 and 2.

substitutions. While the two descriptions may be indistinguishable in many cases, they differ clearly in other cases. For instance, if the patient names the number 17 as 'sixty', should this error be described as the substitution of digits 1 and 7 by digits 6 and 0, respectively, or as the replacement of the word 'seventeen' by the word 'sixty'? In many neuropsychological cases, determining the most adequate description of the errors is crucial because it amounts to identifying the precise functional locus of the deficit. In patient Y.M.'s case, within the chain of visual-to-verbal transcoding mechanisms, did the substitutions arise at a level where numbers were still represented as arabic digits or as strings of words? In our original analysis, we put forward several arguments favouring the hypothesis of digit rather than word substitution (Cohen and Dehaene, 1991). Here, we show how the statistical analysis of perseverations can provide additional evidence as to the level of representation involved. This illustrates the value of perseveration analysis in clarifying the mechanisms of neuropsychological deficits.

As a first step towards separating the influences of digit and word formats on perseverations, all stimuli and responses were coded both in digital arabic notation and as strings of number words. We then performed the same lag distribution and perseveration probability analyses as before, but using the word format. Each erroneously produced word was matched against the words that the patient had used in his previous responses. As is apparent in Fig. 4, word perseverations were present. The perseveration curves were similar to those observed when data were coded in digital format (compare with Figs 1 and 2). There were significant perseverations at least up to lag 3 in both analyses. It may be noted, however, that the effects were less significant in the word analysis than in the digit analysis, perhaps a first indication that the word format is less appropriate for capturing perseverative phenomena. In the lag distribution analysis, for instance, 202 errors were perseverative at lag 1 in the digit analysis compared with only 180 in the word analysis. This suggests that 22 errors could not be accounted for by repetition of a previous word, but made sense in terms of perseveration of a previously produced digit.

To evaluate this hypothesis, we used a two-step process conceptually similar to partial regression. First, the data were run through the word perseveration analysis, and trials that contained errors matching a previous response at a lag shorter than 4 were tagged. In this way we eliminated from the data set all errors that could conceivably reflect a word perseveration. The threshold value of 4 was selected as a conservative value, because the above lag distribution analyses showed significant effects up to a lag of 3. Secondly, the same series of trials was run through the digit perseveration analysis, but only error trials that had not been tagged during the first step were analysed. Thus, we obtained lag distribution and perseveration probability analyses in digital format, restricted to those error trials on which the analysis in word format had identified no perseveration. The results indicated that perseverations remained significant at lag 1 (Fig. 5). Of the 89 errors remaining after elimination of word perseverations, 40 could be matched at lag 1, a value which is significantly higher than the 23.8 matches expected by chance [$\chi^2(1) = 15.0$, $P < 0.001$].

Conversely, when applying the two analyses in the opposite order (tagging in digital format and analysing the residual errors in word format), no residual perseverations were found (Fig. 5B). The lag distribution curve was virtually identical to that expected under the null hypothesis. The perseveration probability analysis did show a single, isolated point of significance at lag 4 [$\chi^2(1) = 7.49$, $P < 0.01$], but, given that there was no effect at lags 1–3, this seemed to be a spurious effect, perhaps related to the large number of statistical tests performed ($n = 8$).

To summarize the findings for patient Y.M., these two-step analyses indicated that there was a significant number of trials in which the patient's responses could be accounted for in terms of perseverations of previously produced digits, but not of previously produced words. We draw two conclusions from these results. First, perseverations were

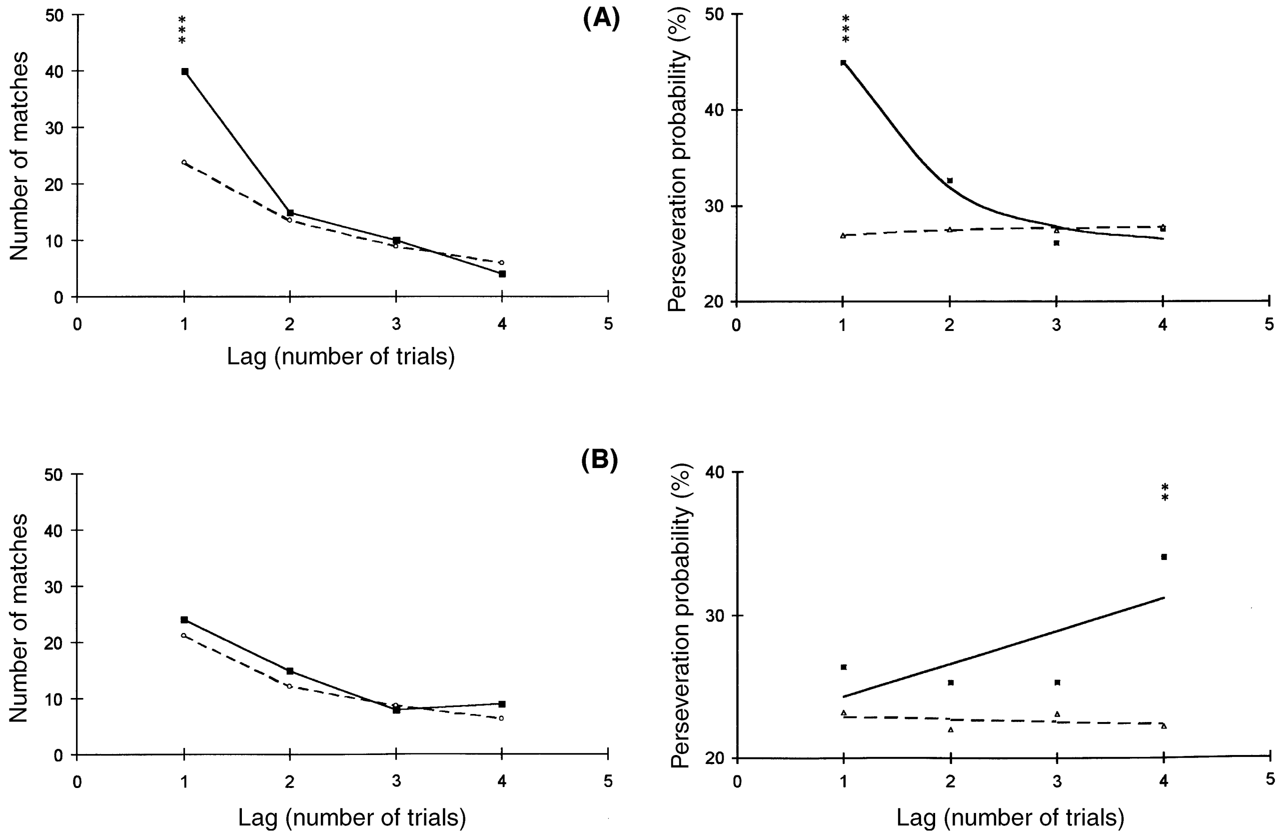

Fig. 5 Lag distribution and perseveration probability analyses of patient Y.M.'s number-reading errors, performed (**A**) in digit format after filtering out word perseverations, and (**B**) in word format after filtering out digit perseverations. Graphic conventions: see Figs 1 and 2.

occurring at a functional stage of the naming process where the numbers were still encoded as digits rather than as words. This fits with other findings in this patient, for instance, his tendency to produce erroneous digits visually similar to the targets (Cohen and Dehaene, 1991). Secondly, from a methodological viewpoint this example illustrates how perseveration analysis can help identify the functional mechanisms underlying a neuropsychological impairment.

Summary

We have provided several examples illustrating the scope and power of a method of perseveration analysis. The main points of interest are (i) the value of the lag distribution analysis and of the perseveration probability analysis for the statistical assessment of perseverations; (ii) the description of their temporal course as a rapidly decreasing exponential; (iii) the influence of previous responses, rather than of previous stimuli, on perseverative responses; and (iv) the importance of the format in which data are coded for the elucidation of the origin of perseverations. In the following two case studies, we apply the same methods of analysis to verbal perseverations originating from different stages of the naming process.

Phonemic perseverations in a patient with neologistic jargon

In the case of patient Y.M., we have shown that perseverations originated from an early stage of the visual-to-verbal translation process, a stage at which visual stimuli were not even yet coded as words. We will now turn to the contrasting case of a patient with phonemic perseverations originating from a late stage of the naming process, namely the final preparation of a phonological plan for verbal output. In order to illustrate the scope of our approach we will show how the same principles of analysis apply to perseverations arising at this processing level.

Case history

Patient D.U.M. was a 76-year-old man who, following a left temporal stroke, suffered from Wernicke's aphasia with severe neologistic jargon. In a detailed study, D.U.M. was asked to name a total of 192 pictures of simple objects, and to read aloud 502 words and 192 non-words (Cohen *et al.*, 1997). Neologisms resulted from pervasive phoneme substitutions, while the overall syllabic structure of targets was generally preserved (e.g. /revolver/ → /reveltil/). Word and non-word

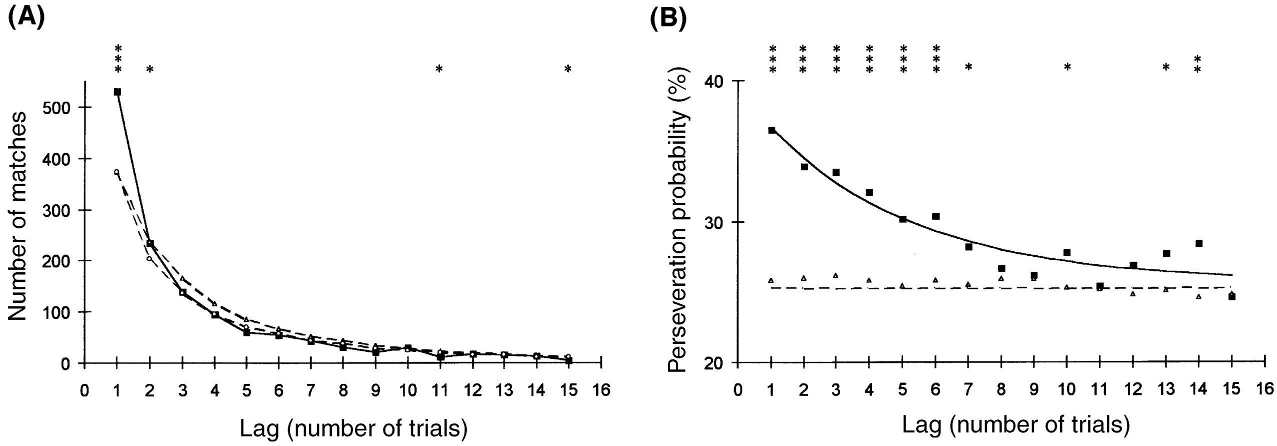

Fig. 6 Lag distribution and perseveration probability analyses of patient D.U.M.'s phonemic errors. Graphic conventions: see Figs 1 and 2.

reading, as well as picture naming, were equally affected, suggesting that errors originated from a relatively late stage of the speech production process, common to all three tasks. The impairment affected the retrieval of the appropriate sequence of phonemes during the planning of speech output (Dell, 1986; Levelt, 1989).

Cohen *et al*. (1997) observed that, when substituting phonemes, this patient showed a general bias for producing more often phonemes that are relatively frequent in French. However, they failed to identify factors predicting which phonemes the patient would choose to produce on a given error trial. They observed only occasional perseverations of a given phoneme over a series of consecutive trials. For instance, while the patient was reading aloud a list that included words and non-words, the phoneme /d/ was erroneously produced in association with a variety of vowels and syllabic structures on 27 out of 38 consecutive trials. It should be stressed that, except for a small number of such series, no perseverations were obvious on purposeful inspection of the data. In an attempt to assess phonemic perseverations objectively, we submitted the corpus of D.U.M.'s naming data to the same type of analyses as described before.

Phonemic perseverations

The analyses were run on phonetic transcriptions of the targets and responses of the whole corpus (886 naming trials, including 591 errors). Each erroneous phoneme ($n = 1489$), i.e. each phoneme that was part of a response but not of the corresponding stimulus, was matched against the phonemes produced on preceding trials (up to a maximum lag of 15).

Figure 6 shows the resulting perseveration probability and lag distribution analyses. Lag distribution analysis showed a significant excess of perseverations at lags 1 ($P < 0.001$) and 2 ($P < 0.05$). Furthermore, perseveration probability analysis showed significant perseverations up to a lag of 7 ($P < 0.001$ at lags 1–6, $P < 0.05$ at lag 7), corresponding to extended sequences of perseverations. Again, the observed perseveration probability curve was remarkably well fitted by a decreasing exponential of the form $PP(L) = \alpha + \beta \times 2^{-L/\tau}$, with the following parameter values: $\alpha = 25.6$, $\beta = 13.8$ and $\tau = 3.2$. This model, which accounts for $r^2 = 89.5\%$ of the variance, indicates that, approximately with every third elapsed trial, the rate of perseverations exceeding chance level is halved. We could thus reveal strong perseverative phenomena, assess their significance and characterize their time-course, while informal inspection of the data did not go beyond the suggestion that occasional perseverations were probably present.

The above analyses were applied without distinction to all trials: all errors were matched with all preceding responses. However, it is possible to perform more selective analyses by considering only a given type of trial in which to look for perseverations, or by matching errors only with a given type of preceding trial. We will illustrate these options by taking advantage of the fact that patient D.U.M. was asked to name words, non-words and pictures.

Perseverations across types of stimuli: words and non-words

Part of the group of stimuli that patient D.U.M. was asked to read aloud consisted of four lists randomly combining an equal number of words and non-words. This set made up a total of 384 trials, including 241 errors. The patient made quantitatively and qualitatively similar phonological errors with the two types of stimuli, suggesting that errors had the same origin in both cases. If this hypothesis is correct, it could be expected that phonemes would be perseverated across types of stimuli. In order to evaluate this prediction, the perseveration analyses were run twice on these data.

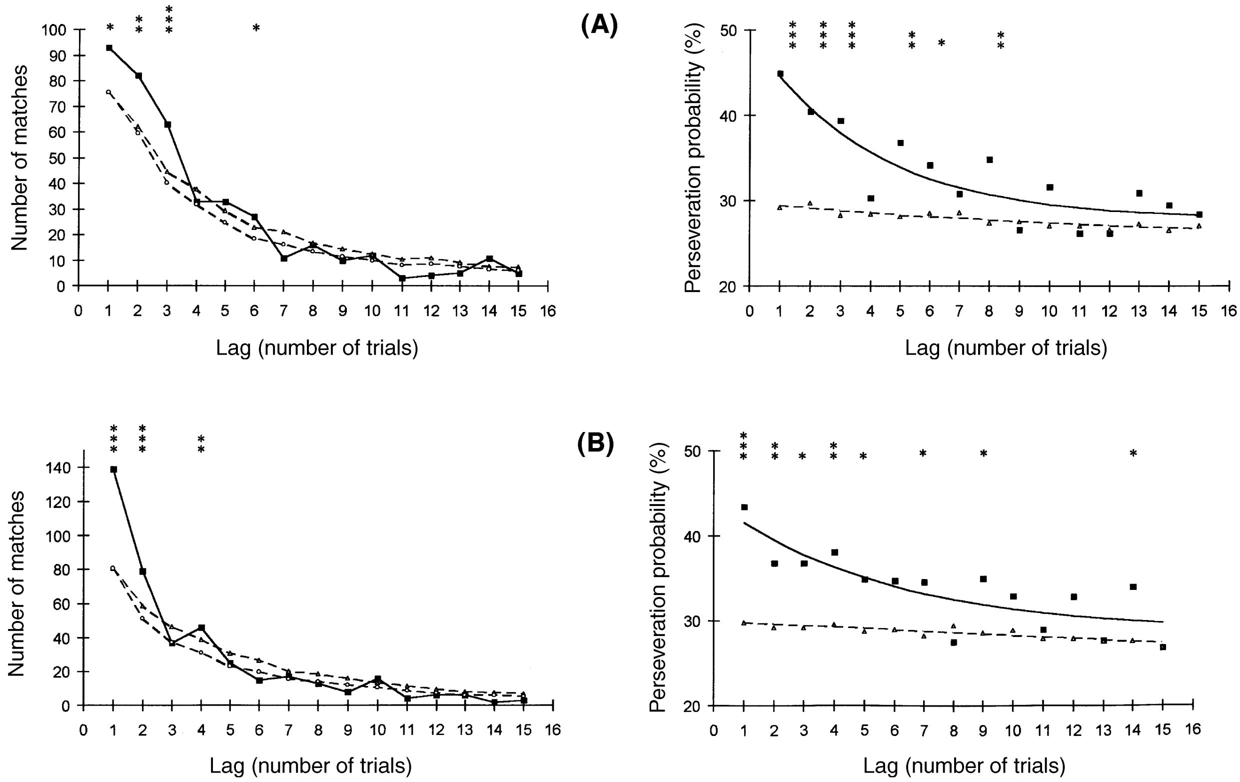

Fig. 7 Lag distribution and perseveration probability analyses of patient D.U.M.'s phonemic errors, performed by matching each error (**A**) with the preceding trials of the same category (i.e. errors with words and non-words were matched with word and non-word trials, respectively), and (**B**) with the preceding trials of the opposite category (i.e. errors with words and non-words were matched with non-word and word trials, respectively). Graphic conventions: see Figs 1 and 2.

First, each error was matched with the preceding trials of the same category (i.e. errors with words and non-words were matched with word and non-word trials, respectively); secondly, each error was matched with the preceding trials of the opposite category (i.e. errors with words and non-words were matched with non-word and word trials, respectively).

We found very significant perseverations in both the within-category and the between-category analyses (Fig. 7). In both cases, significant perseverations were found, up to a lag of about 3 in the lag distribution analysis and a lag of about 8 in the perseveration probability analysis. In other words, phonemes were perseverated across trials irrespective of whether these trials involved words or non-words. This observation conforms with the hypothesis that errors arose at a relatively late stage of the speech production process common to words and non-words.

Perseverations with different types of stimuli: words and pictures

In our first analysis of phonemic perseverations, we did not distinguish trials involving word reading from trials involving picture naming. It is, however, possible that, despite the fact that the error patterns were identical in most respects, perseveration behaviour was different with these two types of stimuli. We therefore performed separate analyses of the word-reading data (310 trials over six experimental lists comprising only words) and of the picture-naming data (one list of 192 trials).

Figure 8 shows that word-reading displayed the expected perseverations, with a significant effect at lag 1 in the lag distribution analysis and up to lag 6 in the perseveration probability analysis. However, no perseverations were revealed in picture-naming. This latter finding was quite unexpected, and we cannot provide a definitive account of it. It may have resulted partly from differences in the time-course of the two experimental tasks: a longer time elapsing between two trials during picture-naming could explain the observation that the residual activation of previous responses was weaker with pictures than with words. However, the perseveration probability analysis showed significant perseverations up to lag 6 with words. Since picture trials were certainly less than 6 times longer than word trials, one would still expect some perseverations to emerge with pictures. Alternatively, this observation may be related to the different cognitive mechanisms involved in the two tasks. In particular, during picture-naming, phonemes can only be activated from the phonological lexicon, while during word-

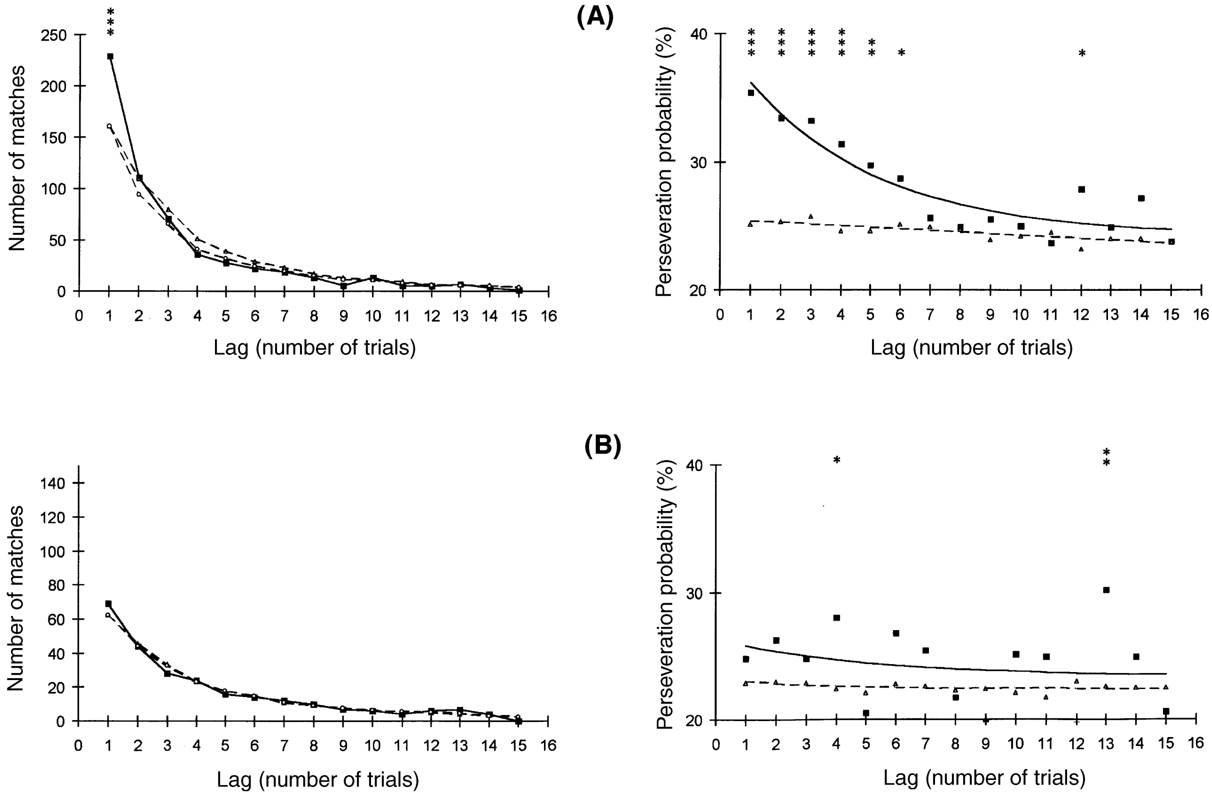

Fig. 8 Lag distribution and perseveration probability analyses of patient D.U.M.'s phonemic errors, performed separately (**A**) with word-reading data and (**B**) with picture-naming data. Graphic conventions: see Figs 1 and 2.

reading there is an additional 'surface' route that directly maps strings of letters into strings of phonemes. At this point we can only hypothesize that this surface route, which was not involved in picture-naming, played a significant role in maintaining persistent activation in previously produced phonemes.

Summary

The study of patient D.U.M. demonstrates that the same methods that were applied to the visual perseverations of patient Y.M. can also be applied to phonemic perseverations, illustrating the wide scope of this approach. The results confirm that the perseveration probability follows an exponentially decreasing time-course. Furthermore, we have shown how analyses restricted to selected subsets of trials can clarify the neuropsychological mechanism of the impairment, and even reveal unexpected findings, such as the absence of perseverations in picture-naming.

Lexical perseverations in a patient with a callosal lesion

In the two patients presented so far, perseverations arose either very early or very late in the course of the naming process, and consisted of the pathological repetition of digits or phonemes from previous trials. We will now turn to a case in which the impairment affects the process of word selection itself. Perseverations consisted of the repetition of previously uttered whole words, illustrating what is usually considered under the heading of verbal perseverations.

Case history

Patient R.A.V. was a 30-year-old woman who, following an infarct of the posterior half of her corpus callosum, presented signs of interhemispheric disconnection affecting the visual, haptic and auditory modalities. In particular, she was severely impaired when reading aloud words and naming pictures that were presented in her left visual field (LVF), a classical consequence of posterior callosal lesions; stimuli that are perceived by the right hemisphere cannot gain access to the left hemisphere, where the verbal response is generated. We observed that, when attempting to name LVF stimuli, the patient often perseverated her responses to previous trials (for a complete description of the case see Cohen and Dehaene, 1996). We studied this phenomenon in word-reading and then in picture-naming.

Word-reading

R.A.V. was asked to read aloud three times a set of 50 mixed words presented tachistoscopically in her LVF or in her right visual field (RVF) over several testing sessions (Table 2).

Table 2 *Patient R.A.V.'s errors in tachistoscopic word-reading and picture-naming*

	Left visual field	Right visual field
Word-reading		
Errors	75/75 (100%)	23/75 (30.7%)
Verbal errors	59/75 (78.7%)	19/23 (82.6%)
Perseverations	38/75 (50.7%)	1/23 (4.3%)
Picture-naming		
Errors	31/43 (72.1%)	6/42 (14.3%)
Verbal errors	20/31 (64.5%)	5/6 (83.3%)
Perseverations	14/31 (45.2%)	2/6 (33.3%)

Box 1

Algorithm for perseveration analysis

```
For each list of trials
  For each erroneous trial T in the list
    Extract the erroneous response E(T) on trial T
    For all lags L up to a maximum of N
      Extract the response R(T – L) on trial T – L
      If E(T) matches R(T – L) Then
        {
        If this is the first match, increment LDA(L)
        Increment M(L)
        }
      Else Increment N(L)
```

The results of this algorithm are LDA(L), the lag distribution, and $PP(L) = M(L)/[N(L) + M(L)]$, the perseveration probability. To compute the chance level for both variables, repeat the above algorithm several times with randomly shuffled lists of trials.

She did not read a single word correctly in her LVF (75/75 errors), while she made 30.7% (23/75) errors in her RVF [$\chi^2(1) = 79.6$, $P < 0.001$]. About 80% of errors consisted of an erroneous word, allowing a simple analysis of verbal perseverations. On three trials the patient successively produced two incorrect response words, both of which were included in the analyses. The remaining errors were failures to respond or unsuccessful attempts at spelling out the target. Almost all RVF errors were confusions between visually similar words (e.g. 'cratère' → 'artère'), and they included only a single perseveration. In contrast, LVF errors were orthographically unrelated to the target, and as many as half of them were repetitions of previous responses (38/75, 50.7%).

Verbal errors to LVF stimuli were submitted to lag distribution analysis, again using a maximum lag of 15. Due to the limited number of trials, lags were grouped in classes of 3. For the same reason, the perseveration probability analysis is not described because of its greater sensitivity to noise in small samples. The number of perseverations observed in the lag distribution analysis was consistently above chance level (Fig. 9). Collapsing over lags 1–12, this effect was highly significant [$n = 30$ versus 17.4; $\chi^2(1) = 15.3$, $P < 0.0001$]. This analysis underestimated the actual frequency of perseverations, because it took into account only local phenomena and ignored some long-term, albeit authentic, perseverations. For instance, during one of the testing sessions, the word 'rateau' was correctly produced on trial 7 and later, erroneously, on trial 28. It seems highly unlikely that the patient selected the erroneous 'rateau' by chance among all French words. This error was thus a probable perseveration from trial 7. However, the lag was as long as 21 intervening trials, and this particular perseveration did not contribute to the statistical measure of local perseverations.

Once the existence of perseverations had been established in patient R.A.V., we attempted to clarify their functional and anatomical origin using more refined analyses. As mentioned before, naming a visual stimulus displayed in the LVF involves (i) processing of the stimulus in the right hemisphere; (ii) transfer of visual and semantic information from the right to the left hemisphere; and (iii) generation of a verbal response in the left hemisphere. Assuming that perseverations reflect a persistent activity of previous responses at some stage in the course of this process, perseverations may in principle originate either from the right or from the left hemisphere. The right hemisphere might maintain pathological long-lasting activation of visual and semantic features of words, perhaps because it never receives a 'check-off' message that the corresponding word has been named. This persistent right-hemisphere activity would then be partially transferred to the left hemisphere, where it would be produced as a repeated response. Alternatively, the persistent activity might reside within the left-hemisphere language production system. Failing to receive adequate stimulus information on LVF trials, the left hemisphere might mistakenly rely on activation from previous trials and hence repeat a previous response.

These alternative hypotheses make contrasting predictions concerning which stimuli enter into perseverations. If perseverations originate from persistent activity within the right hemisphere, then perseverative responses should never be traceable back to a RVF stimulus, which contacts only the left hemisphere. The perseverated words should first appear on an incorrect LVF trial. Alternatively, if perseverations originate from the deafferented left-hemisphere language production system, then they should be influenced by previous trials with both LVF and RVF stimuli, since both types of trials require left-hemisphere processing for the production of a verbal response.

In order to discriminate among these hypotheses, we counted separately perseverations whose closest match was with an LVF trial and those whose closest match was with an RVF trial, and performed lag distribution analysis for each. Almost half of the perseverations matched a preceding RVF trial (17/38, 44.7%), confirming that perseverations originate from a stage common to RVF and LVF trials, i.e. from the left hemisphere. Close inspection of the patient's behaviour suggests that indeed RVF trials played a major role in the initiation of perseverations. A large majority of perseverations (29/38, 76.3%) could be traced back to a

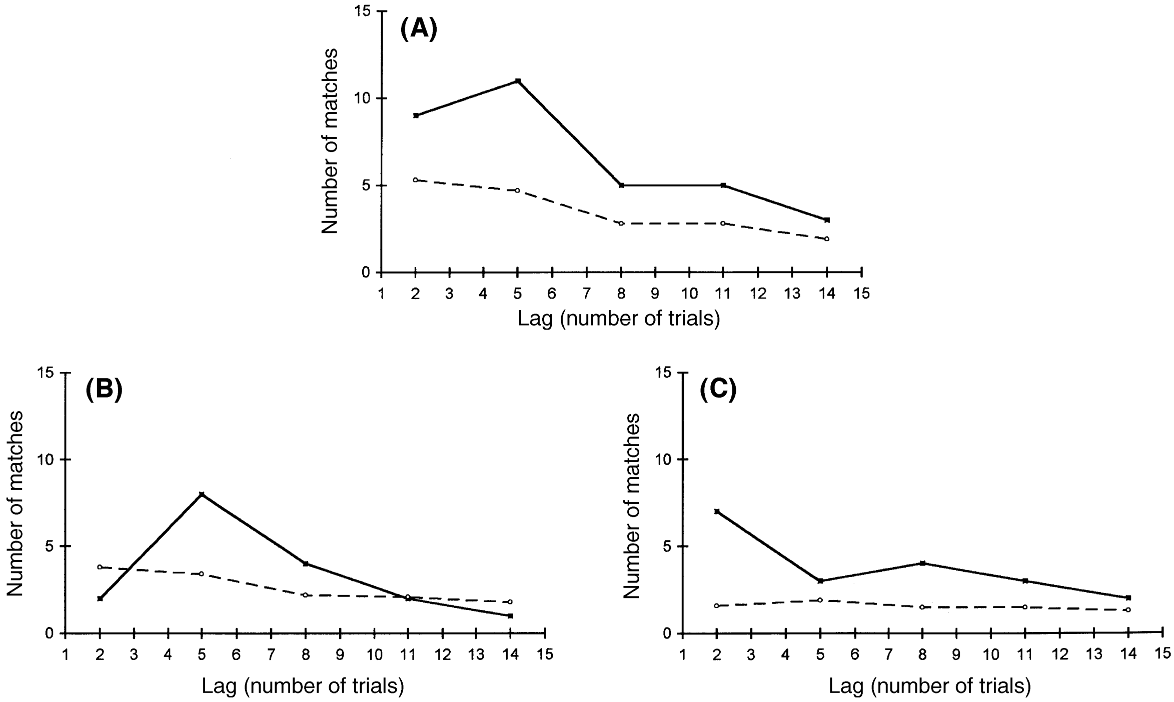

Fig. 9 Lag distribution analysis of patient R.A.V.'s reading errors with LVF words, performed by matching errors (**A**) with all previous trials, (**B**) only with previous LVF trials, and (**C**) only with previous RVF trials. Graphic conventions: see Fig. 1.

correct RVF trial, either immediately or with other intervening perseverations on LVF trials. As a typical example, R.A.V. correctly named the stimulus 'lion' on RVF trial 26, and then perseverated on LVF trials 29 and 42. Interestingly, although the amount of data was too limited to allow a reliable statistical assessment, the lag distribution analysis (Fig. 9B and C) suggested that very short lags (1–3) were frequent with perseverations from RVF trials and infrequent with perseverations from LVF trials, and that conversely lags 4–6 were frequent with perseverations from LVF trials and infrequent with perseverations from RVF trials. In other words, series of perseverations often started from a correct RVF trial, shortly followed by a first perseverative LVF trial, and then other perseverations separated by longer lags. [Although any interpretation of this tendency should clearly remain speculative, it may reflect the multiplicity of codes in which words are represented in the deafferented left hemisphere. On correct RVF trials, targets are processed within the left hemisphere at the visual, semantic, lexical and phonological levels. Persistent activation at each of these various levels may potentially induce perseverations. Note that the different types of perseveration would be very difficult to distinguish from one another, most of them taking the form of full-word repetitions. It is likely that some of patient R.A.V.'s perseverations indeed originated at the semantic level, as suggested by her occasional repetition of generic terms such as 'an animal' in her naming attempts. In contrast, on erroneous LVF trials responses are generated at some intermediate level of the naming process (e.g. the lexicon), leaving a pattern of persistent activation across representation levels that is different from RVF trials. This discrepancy may explain the subtle differences in the time-course of perseverations from RVF and LVF trials, as suggested by the lag distribution analysis.] In brief, most perseverations reflected the persistent activity, in the verbal system, of a word initially produced correctly on a RVF trial.

Picture-naming

Errors in word-reading and picture-naming in the LVF both resulted from the partial deafferentation of the left hemisphere from right-hemisphere input. Assuming that perseverations resulted from the activity of the deafferented left hemisphere, one would expect that exactly similar perseverations should occur in both tasks, even though words and pictures are probably not processed identically within the right hemisphere.

The patient was asked to name 85 drawings of simple objects presented tachistoscopically in her LVF or RVF at random (Table 2). She made 31/43 (72.1%) errors with LVF stimuli and 6/42 errors (14.3%) with RVF stimuli. Indeed, despite the limited size of our data set, the characteristics of perseverations were remarkably similar with words and pictures.

First, as in word-reading, about half of the LVF errors were perseverations (14/31; 45.2%). The lag distribution analysis, collapsed over lags 1–12, was again highly significant [$\chi^2(1) = 14.8$, $P < 0.001$] (Fig. 10A). Secondly, out of the 14 perseverations with LVF stimuli, six could be traced back to a previous RVF trial and eight to an LVF trial.

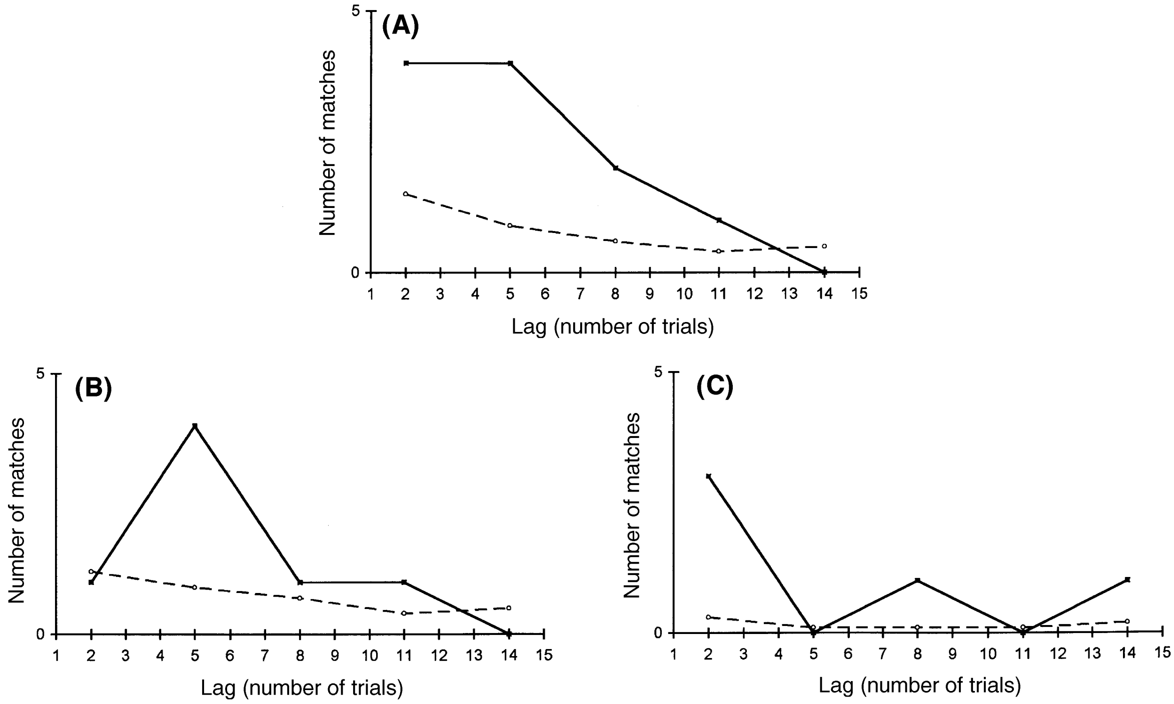

Fig. 10 Lag distribution analysis of patient R.A.V.'s naming errors with LVF pictures, performed by matching errors (**A**) with all previous trials, (**B**) only with previous LVF trials, and (**C**) only with previous RVF trials. Graphic conventions: see Fig. 1.

Thus, as in word reading, RVF trials had an influence on perseverations, suggestive of a left-hemisphere mechanism. Finally, even such a subtle feature as the distribution of lags of perseverations from LVF and RVF trials followed the same pattern with pictures as with words (Fig. 10B and C, to be compared with Fig. 9B and C): very short lags (1–3) were frequent with perseverations from RVF trials and infrequent with perseverations from LVF trials, while lags 4–6 showed the opposite distribution.

Summary and discussion

While perseverations in patients Y.M. and D.U.M. originated from an early visual stage and a late phonological stage of the naming process, respectively, the case of patient R.A.V. illustrates verbal perseverations in their most typical sense, i.e. perseverations of whole words. We have shown how an internal analysis of perseverations, and particularly of the role of RVF and LVF trials, provided independent evidence for a left-hemisphere locus of the persistent activity. Perseverations resulted from remaining activity left over from previous trials within the intact but disconnected, language-dominant, left hemisphere. This simple conclusion suggests the hypothesis that deafferentation by itself may be essential, and possibly sufficient, to induce perseverations in a system deprived of its normal input. This idea is at the core of the theoretical proposal formulated in the following section.

General discussion

In this general discussion, we first summarize the methodological principles that we have proposed for the quantitative analysis of perseverations, and the main empirical results that were obtained with these methods. We then attempt to frame a theoretical proposal concerning the common mechanism that could be at the origin of the various types of verbal perseveration that we have described.

Methodological summary

The two basic methods of analysis that we propose are the lag distribution analysis and the perseveration probability analysis. Both can be considered as variants of the same algorithm (Box 1). This algorithm was applied many times during the study of our three patients. However, the techniques had to be adapted each time according to the type of data, to the hypothesis to be tested, etc. We now briefly review the parameters that must be set prior to any such analysis. In other words, what are the main questions one should ask when planning the analysis of a corpus of errors? (i) Should we look for perseverations in *all* error trials? The analysis may apply to all trials, but can also be restricted to a given subset of trials. For instance, in the case of patient R.A.V. analyses were restricted to error trials with a LVF stimulus. (ii) Should we consider the possibility of several errors occurring on a single trial? First, the patient may spontaneously propose several erroneous responses or autocorrections on a single trial, as was occasionally the case with patient R.A.V. Secondly, and more importantly, a single response may itself comprise several errors. For instance, the neologisms produced by patient D.U.M. often included several erroneous phonemes, which were considered as independent errors. (iii) To what maximum lag should we choose to backtrack when attempting to match errors with previous trials? Here we used a maximum lag of 15 trials, a value which seemed sufficient to capture most relevant phenomena. (iv) In order to decide whether an error is a perseveration or not, should we try to match it with *all* previous trials (up to the maximum lag)? We have shown that it may be useful to restrict the matching process to a given subset of trials, especially when trying to trace back the origin of perseverations. This subset can be defined on the basis of some fixed property. For instance, in the case of patient R.A.V. errors were matched selectively either with LVF or with RVF trials. Alternatively, the subset can be defined on the basis of some relationship with the error trial. For instance, in order to decide whether patient D.U.M.'s phonological perseverations could span across words and non-words, we matched errors only with preceding trials of the same type, or only with preceding trials of the opposite type. (v) On what criteria should we decide that an error matches a preceding trial? A first option is to require an exact match. For instance, in the case of patient R.A.V. verbal errors had to be identical to a previous response in order to be considered as perseverations. Alternatively, one can look for partial matches. For instance, in the case of patient D.U.M. we examined whether erroneous phonemes were *part of* the preceding responses. Finally, errors can be matched with previous responses, but also with previous stimuli. We have demonstrated the superiority of matching with previous responses in the case of patient Y.M. (vi) In what format should the data be coded? This issue may have a significant effect on what counts as an error. For instance, in the case of patient Y.M. the reading of 17 as 'sixty' corresponds to one or two errors depending on whether data are coded in word format or in digital format. Furthermore, we have shown that the number and distribution of perseverations also depends on the format selected.

Summary of empirical results

With the above methods, the following empirical results were established.

Level of processing

We observed perseverations of whole words (patient R.A.V.), but also of single phonemes (patient D.U.M.) and of single digits in a multidigit number-naming task (patient Y.M.). This suggests that perseverations can arise from any of several levels of processing.

Exponential decay

At any processing level, the probability that an error is a perseveration from a previous trial is a decreasing function of the lag between the two trials considered. This suggests that an exponentially decaying internal variable, such as an internal level of activation, is responsible for the recurrence of perseverations. Two qualifications are in order, however. First, our methods may fail to detect small but prolonged perseveration effects that would extend beyond the initial exponential period (e.g. patient R.A.V.). Note that, in normal subjects, small but enduring effects of repetition priming have been revealed even when the prime and the target are separated by considerable lags (Wheeldon and Monsell, 1992; McKone, 1995). Secondly, a specific experiment would be needed to distinguish the effects of elapsed time versus elapsed number of trials on the decay of perseveration probability. [Lhermitte and Beauvois (1973) report that, in their optic aphasia patient, perseverations bridged over interruptions of up to 1 min in the serial naming task.]

Depth of processing

A necessary and sufficient condition for a given item (e.g. word or phoneme) to be liable to perseveration on subsequent trials is for that item to be explicitly produced by the patient. Thus, responses may perseverate (be they correct or incorrect), whereas stimuli that are not read correctly do not (patient Y.M.). When perseverations occur at the phoneme level (patient D.U.M.), phonemes first produced in the context of a word may recur in the context of non-words. Likewise, in a split-brain patient (R.A.V.) words read correctly on RVF trials can later become perseverated responses on LVF trials.

A general theory of verbal perseverations

Based on these empirical results, we submit a tentative theoretical mechanism for the generation of perseverations. Our proposal may be summarized as follows: (i) persistence of activity from previous trials is a normal feature at many levels of the processing system; (ii) in normal subjects this persistent activity is overruled by the current input and is therefore not readily observable; (iii) whenever a processing level is deafferented from its normal input source, persistent activity is no longer systematically overcome by the current input and can exert a major influence on behaviour; hence, perseverations occur; (iv) the format of the perseverations (e.g. phonemes, words, etc.) corresponds to the specific format of the deafferented level, explaining the various types of verbal perseverations. In a nutshell, we suggest that perseverations result from persistent activity unmasked by deficient input. These points will now be discussed in turn.

Persistence in normal word production

Persistence of activation is a normal feature of the language processing system, as it probably is of many other neural systems. We will review some experimental data that reveal the effects of such persistence in the domain of speech production, with special emphasis on the level of word selection.

In normal subjects, what are the factors that govern the eventual selection of a response word during a visual naming task? According to parallel processing theories, all words in the mental lexicon simultaneously receive activation from the conceptual system. Only the first word whose total activation reaches some absolute firing threshold, or exceeds the activation of all other words by some differential criterion, is eventually selected for output (e.g. Morton, 1979; Dell, 1986; McClelland and Elman, 1986). Once a word has reached the threshold, its activation decays spontaneously to a resting level. However, the amount of activation that it receives from outside the lexicon is not the only factor that governs the probability that a given word is selected on a naming trial. Two additional influences, internal to the lexicon, should be mentioned. First, it has been suggested that words differ in the intrinsic speed with which they reach their firing threshold, depending in particular on their frequency of use (Wingfield, 1968; Jescheniak and Levelt, 1994). Secondly, and more importantly in the present context, words may still enjoy, at the outset of a naming trial, some of the activation accumulated during the preceding trials and not yet dissipated through spontaneous decay. The larger this residual activation, the closer a word to its threshold, and hence the higher its probability of being selected on the current trial.

Such enduring phenomena have been demonstrated mostly in the form of priming effects and of speech errors. Priming effects include both facilitation (reduced latencies and error rates) and inhibition (increased latencies and error rates) in serial picture- or word-naming tasks. Thus, naming an object is facilitated when the name has already been produced recently, in the context of picture-naming, word-reading or naming on definition (Wheeldon and Monsell, 1992). The production of a word is also facilitated, although over a shorter time lag, by the previous utterance of a semantically related item (e.g. Loftus, 1973; Huttenlocher and Kubicek, 1983; Humphreys *et al*., 1988). Conversely, the production of a word can be inhibited by the previous utterance of a related word that acts as a potential competitor (Wheeldon and Monsell, 1994). In addition to such priming effects, normal subjects may, under special conditions, produce recurrent utterances akin to pathological perseverations. When subjects are required to name pictures under stressful time pressure, they tend to produce semantically related errors that have been appropriately produced on previous trials (Vitkovitch and Humphreys, 1991). Similarly, when asked to solve as rapidly as possible simple arithmetic problems, subjects occasionally answer erroneously by repeating the answer to a previous similar problem (Campbell and Clark, 1989; Campbell, 1991). Note that this latter effect follows an exponential decay perceptible over about 10 trials. Finally, although we are mainly interested here in persistent effects in word production, one should remember that similar phenomena have been observed with tasks involving word recognition. For instance, McKone (1995), measuring reaction times in a lexical decision task, obtained repetition priming effects whose exponential time-course over several trials was remarkably similar to our own perseveration curves (Fig. 11).

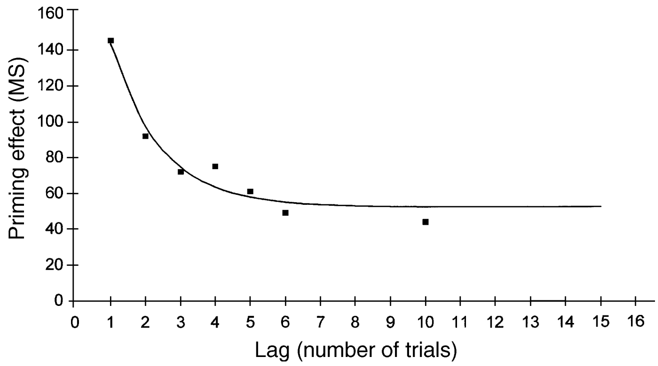

Fig. 11 Repetition priming effect on reaction times in a lexical decision task, as a function of the lag between the prime and the target (data from McKone, 1995). Actual data are fitted by a decreasing exponential curve.

Persistent effects in normal language production are by no means restricted to the level of word selection. They also appear at 'lower' and 'higher' levels of speech planning. Clear evidence for persistence in phonological encoding comes from the analysis of spontaneous or experimentally induced speech errors (Levelt, 1989). Perseverations, i.e. contamination of current output by phonological fragments of previous words, are a well documented type of error in normal subjects [e.g. 'beef needle' instead of 'beef noodle' (Fromkin, 1971); 'they needed to be maded' instead of 'they needed to be made' (Shattuck-Hufnagel, 1979)]. Such phenomena reflect the persistent activation of phonological fragments after the point at which they normally occur in the speech stream (Dell *et al*., 1997). Although we are concerned here with the processing of single words, it may be interesting to mention that perseverative effects in normal language production have also been demonstrated at the level of syntactic planning. In a series of studies, Bock showed that, after having produced a sentence with a given syntactic structure, subjects are unconsciously biased towards using the same structure again when describing subsequently presented pictures (Bock and Loebell, 1990). Finally, priming effects across trials are not restricted to the language-related components of the naming tasks, but also occur at the early, visual stages of the processing chain (Biederman, 1990).

In brief, persistent effects are discernible at essentially all stages of the naming process. The very existence, in normal subjects, of exponentially decaying priming effects that last over several trials, as exemplified by the data of McKone (1995) (Fig. 11), is of great consequence for interpreting the verbal perseverations produced by brain-damaged patients. It suggests that the persistent activation of words in the lexicon that underlies perseveration is indeed a normal phenomenon. (We are not committed here to any specific network theory of speech production. What we describe formally as the persistent activation of words in the mental lexicon may reflect various underlying neural mechanisms, such as persistent modification of the firing of groups of neurons, strengthening of their synaptic connections, or yet other mechanisms for long-lasting alterations of their activation function.) The role of the neuropsychological impairment would not be to generate a protracted activation of previous utterances, but only to reveal this persistent activity in the abnormal form of overt perseverations.

Perseverations as a consequence of deafferentation

In normal subjects the residual activation inherited from foregoing trials is small in comparison with the activation pattern induced by the current stimulus; perseverative errors in normal speech are very rare, and delicate techniques are required to reveal priming effects. What are the circumstances in which previously uttered speech elements overcome the new expected output and are produced again? We will show how deafferentation may constitute one such circumstance.

Whenever some processing level is at least partially deprived of its normal input sources, i.e. deafferented, the representation of the current stimulus at this stage is absent or abnormally weak. In such cases, faded activation patterns inherited from past trials acquire a predominant influence on the deafferented level. In a serial naming task, this results in abnormal contamination by previously emitted responses, i.e. perseverations.

At first sight this hypothesis accounts easily for the behaviour of patient R.A.V. Contrary to the two other patients, her left hemisphere, including the language system, was essentially intact. She only suffered from a lesion of her corpus callosum, inducing a pure deafferentation of the left hemisphere from visual inputs presented to the right hemisphere. Hence, as demonstrated by the above analysis, the left hemisphere perseverated previously emitted responses. Verbal perseverations similar to those of patient R.A.V. have been observed regularly in several related disorders resulting from left occipitotemporal and callosal lesions, and involving visual deafferentation of the left hemisphere (De Renzi and Saetti, 1997), including optic aphasia, associative visual agnosia and pure alexia (Lhermitte and Beauvois, 1973; Iorio et al., 1992; Plaut and Shallice, 1993; Cohen and Dehaene, 1995). It may be noted that in such cases whole words, but also isolated semantic features, can be perseverated across trials. For instance, 'a paint brush presented after a piece of fuse wire was identified as an electric plug' (Ettlinger and Wyke, 1961), indicating that the concept of 'electrical device' was perseverated rather than a specified word. In some cases perseverations may even spread beyond the domain of single-word selection and contaminate the whole discourse and even the gestural behaviour of patients engaged in an object-naming task (Hudson, 1968; Marin and Saffran, 1975; Papagno and Basso, 1996).

Can we interpret the performance of our two other patients along the same lines? Let us turn first to patient Y.M. Our interpretation of his reading deficit is that he suffered from impaired visual processing in his left hemisphere, leading to an ill-formed visual number form and hence to reading errors. Thus, we assumed that the locus of the impairment was just upstream from the visual number form. The visual number form lacked an adequate input and, as a consequence of this deafferentation, displayed perseverative behaviour. Again, the format of the perseverations, i.e. digits, corresponded to the format in which stimuli are represented at the deafferented level.

The same account also applies to the case of patient D.U.M. When producing phonological paraphasias, he actually selected the correct word but made a variable proportion of errors in the subsequent selection of phonemes when planning speech output. Thus, the deficit occurred just prior to the phonemic level of representation, which was deafferented (Cohen *et al*., 1997). As a consequence, some phonemes from previous trials were not overruled by phonemes from the current target, and resurfaced in the form of perseverations. Again, the format of the perseverations, i.e. phonemes, corresponded to the format in which stimuli are represented at the deafferented level.

Competition between past and present

A proposal similar to ours has been put forward recently by Dell *et al*. (1997) and Schwartz *et al*. (1994) in the context of their parallel processing model of speech production. They discuss the issue of serial ordering in speech planning, with emphasis on anticipation and perseveration errors. Actually, Dell *et al*. (1997) studied ordering *within* hierarchically organized units of speech (phonemes within words or words within clauses) whereas here we consider perseverations *across* unrelated successive naming trials. However, some of the general concepts that they develop may apply to the present issue. Their argument is centred on the competition, at each moment, between the past, present and future elements of the speech stream. Perseverations occur whenever the present element is activated less strongly than previous elements. The main claim of Dell *et al*. (1997) is that the relative proportion of perseverations among ordering errors should increase in various circumstances in which the strength of input connexions from the preceding representation level is thought to decrease: lack of practice, increased speech rate, brain damage (Schwartz *et al*., 1994). This proposal is akin to our own hypothesis that deafferentation may be a crucial condition for perseverations to occur.

It should be stressed that we do not claim this mechanism to be the only possible source of perseverations in patients. It is quite conceivable that previous responses remain activated at an abnormally high level, due in particular to impairment of some inhibitory or check-off mechanism (Shattuck-Hufnagel, 1979). For instance, Campbell (1989, 1991) shows that in normal subjects a short-lived inhibitory effect is superimposed on the protracted decaying persistence of previous responses. Hence, perseverations actually occur at a rate lower than chance level at very short lags in

Campbell's data. It is also possible that patients with impaired self-monitoring of their speech output may fail to 'edit out' some perseverative responses compared with normal subjects (Levelt, 1989). Interestingly, the debate between 'passive' accounts of perseverations (Pick, 1903), such as ours, and more 'active' theories dates back to the origins of this field of research (Hudson, 1968). Pick (1903), commenting on the perseveration of the word *locksmith*, claimed that 'due to the weakness of the [present] associations, the representation of *locksmith*, which remained since the previous test below the threshold of consciousness, but available to it, crosses the threshold . . . . This representation is therefore *relatively* strengthened and can remain so for a certain amount of time.' In our explanatory proposal, i.e. normal persistence plus deafferentation, we put emphasis on a minimal mechanism for perseverations. While this may not be the only mechanism, we believe that it is sufficient to account for a wide variety of pathological situations.

Generalization to other domains

In conclusion, one may speculate about the scope of this approach beyond the domain of speech processing. Persistence of activation and deafferentation may in principle affect a variety of other cognitive systems, and may account for other kinds of perseverations. For instance, cognitive models of limb movement have been proposed that are highly similar to standard models of word processing, featuring modules such as action input and output lexicons (Rothi *et al.*, 1991). It is conceivable that the same general mechanisms studied here in the domain of verbal perseverations may apply to some extent to recurrent gestural perseverations that are produced by some apraxic patients (MacKay, 1985). Is it also possible to draw a parallel between the present situation and higher-level 'frontal' perseverations? Shallice (1982, 1988) propose that action control results from the combination of elementary stored action routines or schemata, which are selected both by bottom-up activation from sensory processing (or Contention Scheduling) and by top-down modulation from a (prefrontal) Supervisory System. In particular, the Supervisory System is needed whenever the currently active schema needs to be inactivated (in the absence of bottom-up triggering of a concurrent schema). Thus, when frontal lobe patients performing the Wisconsin Card Sorting Test perseverate on the previously correct rule 'it is the schema controlling internal programming that remains fixed, . . . the type of perseveration . . . that one would expect if a Supervisory System is damaged' (Shallice, 1988, p. 342). In other words, behavioural rigidity would result when persistent action schema are deafferented from the Supervisory System. If this model can be validated, the statistical and theoretical tools that we have developed might provide a synthesis of the various perseveration phenomena and open up new paths for their rigorous experimental study.

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