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How damaged brains repeat words: A computational approach

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Abstract

Two routes have been proposed for auditory repetition: a lexical route which activates a lexical item and retrieves its phonology, and a nonlexical route which maps input phonology directly onto output phonology. But when is the nonlexical route recruited? In a sample of 103 aphasic patients, we use computational models to select patients who do and do not recruit the nonlexical route, and compare them in light of three hypotheses: 1-*Lexical-phonological hypothesis:* when the lexical route is weak, the nonlexical route is recruited. 2-*Nonlexical hypothesis:* when the nonlexical route is weak, it is abandoned. 3-*Semantic-access hypothesis:* when access to meaning fails, the nonlexical route is recruited. In neurocognitive terms, hypotheses 1 and 2 identify different aspects of the intactness of the dorsal stream, while the third hypothesis focuses on the ventral stream. Our findings (and a subsequent meta-analysis of four studies) support hypotheses 2 and 3. Ultimately, we claim that the choice about whether to recruit the nonlexical route is guided, not by assessment of production abilities that support repetition, but instead by relying on accessible cues, namely whether the speaker understands the word, or can remember its sequence of phonemes.

1. Introduction

Repeating back a spoken word is an easy task for healthy adult speakers, and rarely results in error. On the other hand, aphasic patients have varying degrees of difficulty with auditory word repetition, and studying these deficits can inform us about the cognitive and neural architecture of word repetition. Generally, word repetition assesses the patient's ability to assemble phonology. Two cognitive routes have been proposed for this: One is a *lexical route* (e.g. Dell, Martin, & Schwartz, 2007; Gupta & MacWhinney, 1997; Hanley, Kay, & Edwards, 2002; Hillis & Caramazza, 1991) in which, after recognizing the input word, its lexical entry is accessed, and then its phonology is retrieved in the same manner as if one had retrieved the word from its meaning. The production part of the lexical-route model of repetition, thus, uses a subset of the processes that would be used, for example, to name a picture.

The other route is a *nonlexical route* (Gupta & Tisdale, 2009; Hanley et al., 2002; Hanley, Dell, Kay, & Baron, 2004). Instead of accessing lexical items, this route maps a representation of the input (input phonology) onto the phonological representation that guides speaking (output phonology). Because no lexical item is recognized, this route is

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particularly suited for the repetition of nonwords. Studies of how aphasic individuals repeat words have demonstrated that the nonlexical route, by itself, cannot accurately characterize aphasic repetition; for example, repetition is nearly always considerably worse for nonwords than words (e.g. Dell et al., 2007), thus contradicting the straightforward prediction from a purely nonlexical repetition model that words and pronounceable nonwords would be equally easy. Instead, it seems that the nonlexical route acting in concert with the lexical route may be the correct model for many patients (Hanley et al., 2002; Hanley et al., 2004). The model combining the lexical and nonlexical routes is called the *dual-route* repetition model. In general, a fair amount of evidence points to the conclusion that many patients repeat words according to the dual-route model, but performance of some are best explained by the lexical-route model (see Nozari, Kittredge, Dell, & Schwartz, 2010, for review).

The conclusion that patients vary in which model governs their word repetition may be accurate, but it is ultimately unsatisfactory. We would like to know what determines whether the lexical route alone is used, or whether the nonlexical route is recruited. We investigate this issue by selecting patients who appear to use only the lexical route (lexical-routers), vs. the ones who appear to use both routes (dual-routers) and comparing them. Our approach involves a computational treatment of the models. We first use computational models to select patients from a large aphasic database (Mirman, Strauss, Brecher, et al., 2010) who are clear lexical- or dual-routers, thus defining a contrastive two-group sample. Next, we use those models and other considerations to generate and test hypotheses about the differences between the two groups, with the aim of drawing conclusions about why the groups differ in their approach to word repetition. Finally, we test our conclusions by looking at a separate set of patients in a meta-analysis of previously published cases.

1.1. Using models for patient selection

The computational implementations of the lexical-route and dual-route models are derived from a model of lexical access in language production that explains aphasic picture naming (e.g. Dell et al., 2007; Nozari, et al., 2010). Specifically, knowing patients' pattern of response in picture naming is enough to estimate their repetition performance if repetition occurs through the lexical route, because the latter is part of the former's architecture, assuming that recognition of the incoming word is intact. In the naming model (Fig. 1, upper panel), picture naming is divided into two steps: Step 1) accessing words from semantic features. How well this step is accomplished depends primarily on the strength of the connections between semantics and words (parameter S in the model, or S *weights*). Step 2) accessing phonology from words. Success of this step depends most on the strength of the connections between words and phonemes (P *weights* in the model).

Picture naming in the model begins with a jolt of 100 units to the semantic features of the pictured object (e.g. for the target *cat*, ‘furry’, ‘feline’, ‘meows’). The activation spreads in the network, and after 8 cycles, step 1 ends by choosing the most activated node in the word layer (e.g. ‘cat’), which consists of the abstract representation of words without their phonology (i.e. lemma; Kempen & Huijbers 1983). This selected node, then receives a boost (a jolt of 100 units) of activation, and the second step starts by again spreading activation within the network. Picture naming is completed when after 8 cycles, the most highly activated phonological nodes are selected (e.g. ‘k’, ‘æ’, and ‘t’).

When the S and/or P parameters are low, the model is error-prone. In fact, this is how the model simulates aphasic production (e.g. Dell, et al., 1997). For example, a lower S parameter may lead to the selection of a semantically related word (e.g. *dog* for *cat*), because semantic features do not send enough activation to the word level for the target word to stand out over semantically similar ones. Or a weaker P may lead to the choice of the wrong phoneme (‘h’ or ‘z’ instead of ‘k’), resulting in the production of the wrong word/nonword ('hat' or 'zat' for 'cat'). By looking at how many errors and of what type a patient makes in the picture naming task, it is possible to estimate parameters S and P.

Lexical-route repetition is viewed as simply the second step of naming (Fig. 1, lower panel, the left-side figure), and therefore, can be predicted through parameter P[1]. It is assumed that once a word is recognized, all that is required for its production is activating its phonology. In the model, this is achieved by giving the to-be-repeated word – instead of its semantic features– a jolt of 100 units of activation, and letting the model complete the second step of naming in 8 cycles. Retrieving the phonology is equivalent to generating a repetition response. Critically, predicting lexically-mediated repetition from naming is a parameter-free prediction. Once the values of P and S are determined from naming data, one can run the model's phonological access step (Step 2) and get the predicted repetition from the lexical route.

In the same vein, it is possible to predict repetition performance via a dual-route model. However, a little more information is needed, as the dual-route model has both a lexical and a nonlexical part to it (Fig. 1, lower panel, the right-side figure). The nonlexical route is a path separate from the naming architecture. Its role is to directly map the input to output phonology. This route is essential to language learning, and both children and adult speakers learning a novel language use it (e.g. Gathercole, 1995; Gathercole, Willis, Baddeley, & Emslie, 1994; Plaut & Kello, 1999). By definition, nonwords do not have lexical entries in the language system, and as such cannot be fully processed through the lexical system. We simulated the nonlexical route by creating a temporary node, representing a temporary buffer for the input. This node is similar to the existing word nodes in the lexicon, and like such nodes, has bidirectional connections to its phonology, and its activation is subject to decay through the 8 cycles of mapping. The strength of the connections between the temporary node and the output phonology is represented with parameter NL which, similar to the S and P parameters, can be estimated from patients' empirical response patterns. Specifically, NL is estimated by fitting the model to the response pattern in a nonword repetition task.

Once the parameter NL is obtained through the nonword repetition test, in combination with parameters S and P, one has all the information needed to make predictions about the accuracy of word repetition through the dual-route model. The lexical part works exactly as described in the lexical-route model, by giving a jolt of 100 activation units to the lexical node of the to-be-repeated item. Simultaneously the nonlexical part is run, by giving a jolt of 100 units to the temporary node, now set to the input word, connected to its relevant phonology in the output phoneme layer. The final result is a summation of the output of both routes (See Nozari et al., 2010 for reasons to accept the summation dual-route over alternative dual-route models).

The dual-route word repetition model was initially only developed as a cognitive model. Recently, Dell et al. (in press) found the neural correlates of the dual-route repetition model in the brain. Using voxel-based lesion-symptom mapping (VLSM, Bates et al., 2003) in a large sample of patients with chronic aphasia from left hemisphere stroke whose lesion locations had been determined, Dell et al. first showed that behavioral scores in an auditory word repetition task correlated significantly with lesions in the superior temporal gyrus, supramarginal gyrus, area Spt, post-central gyrus, and an extension into inferior frontal gyrus. Next, using the same technique, they investigated the neural correlates of the model

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[1] All the models used in this paper are 'interactive', meaning there is feedback from lower to higher layers. This means that technically, parameter S does influence repetition through the lexical route. However, this influence is small compared to the other parameters discussed.

parameters (S, P, and NL). They then showed that, in keeping with the cognitive model, auditory word repetition is a “summation” of the P and NL parameters by showing that the brain map associated with the sum NL+P was very similar to the map for word repetition. Individually, the NL and P parameters were both associated with central parietal areas and the supramarginal gyrus. The two parameter maps differed, though, with NL more associated with the more posterior of the regions mentioned, including area Spt, and superior parts of the temporal cortex, and P more extending anteriorly to inferior frontal gyrus. In terms of Hickok and Poeppel's “dual stream” neurocognitive model of language (Hickok, 2012; Hickok & Poeppel, 2007; Poeppel & Hickok, 2004), both the NL and P parameters, as well as auditory word repetition, nicely mapped onto the dorsal stream, which encompasses auditory-phonological representations in the superior temporal gyri and sulci of both hemispheres (including Wernicke's area on the left), a sensori-motor interface in the posterior portion of the Sylvian fissure at the parietal-temporal junction (area Spt), somatosensory areas in the parietal lobe (e.g. supra-marginal gyrus) and a frontal articulatory network.

The S parameter's brain correlates, in contrast, were both behaviorally and neurally separate from the other two parameters. S localized most strongly to hypothesized semantic and lexical-semantic areas of the anterior temporal lobe and to areas of the frontal lobe that could be involved in controlling lexical-semantic representations (see, e.g. Bedny, Hulbert, & Thompson-Schill, 2007; Schnur, Schwartz, Kimberg et al., 2008; Schwartz et al., 2009; Schwartz, Faseyitan, Kim, & Coslett, 2012). Its mapping was much more consistent with what Hickok and Poeppel (2007) called the ventral stream. The ventral stream is proposed to link auditory-phonological information with lexical and semantic long-term memory representations in the temporal lobe. A specific implementation of the ventral stream by Ueno, Saito, Rogers, and Lambon-Ralph, (2011) further links semantic representations in the anterior temporal lobe to production centers in the frontal lobe. In summary, Dell et al. identified an “NL-P axis” associated with the dorsal stream and auditory word repetition, and an “S axis” associated with the ventral stream that was not, at least directly, involved in auditory word repetition (But see Ueno et al.'s model, which indirectly involves the ventral stream in repetition).

With this background, we turn into the central question of this paper. Which repetition model is used in which patients? For most patients, the lexical-route and dual-route models will make comparable predictions (Dell et al., 2007). However, there are cases where performance is much better predicted by one model than the other. For example, Nozari et al. (2010) reported a survey of four studies (Abel, Huber, & Dell, 2009; Baron, Hanley, Dell, & Kay, 2008; Dell et al., 2007; Hanley et al., 2004), on a total of 82 aphasic patients, and singled out six patients whose word repetition performance was clearly better predicted by the lexical-route model and nine whose performance was much better predicted by the dual-route model. Here, using the models described above, and a large sample of 103 aphasic patients, we do the same.

Table 1 illustrates the steps through which we select the lexical- and the dual-routers. The table presents data from three patients from the Moss database (Mirman et al., 2010), one of whom (Patient A) is determined to be a dual-router (i.e. the dual-route model's prediction for word repetition is accurate and considerably better than the prediction for the lexical route model), one (Patient B) a lexical-router, (the reverse of Patient A's case), and one (Patient C), where it is not possible to tell because of a ceiling effect on word repetition.

The evaluation process has 7 steps. First, the S and P parameters are set so that the model mimics the patient's naming error pattern (Table 1a, b). This is done by selecting parameter values through a maximum likelihood estimation process (e.g. see Dell et al., 2004, for details). With the model set up with those S and P parameters, it is then fit to the patient's nonword repetition performance by adjusting the NL weight, as described in Dell et al. (2007) and Nozari et al. (2010) (Table 1c, d). Then, the entire set of parameters is tested to see whether each model can predict word repetition (Table 1e-g). This is done once for the lexical-route model and once for the dual-route model. It can be seen in Table 1 that the dual-route model is clearly superior to the lexical-route model for Patient A. The dual-route model predicts .91 accuracy, which is close to the patient's actual accuracy of .95. The lexical route model, on the other hand, severely underpredicts Patient A's word repetition[2] by predicting only .65 accuracy. Patient B, in contrast, is a clear example where lexical-route model makes the better prediction. We included Patient C to show that the evaluation for many patients is ambiguous, largely because both models predict that word repetition will be very good (e.g. greater than .95). Note that this does not hint at the failure of the models to predict repetition. It simply shows that when performance is close to ceiling predictions of the two models are too close to pick a superior model. As such, these cases are simply not informative in comparing lexical- and dual-routers, so we exclude them from the analysis.

1.2. Using the models for hypothesis development

Patients differ in whether the lexical-route or the dual-route model best predicts their word repetition, meaning that certain patients rely solely on the lexical route, while others recruit the nonlexical route to boost their repetition performance. What determines this difference? One possibility is that recruitment of a repetition route depends directly on how well that route works. The idea is that patients might be able to assess the quality of their lexical and nonlexical routes and choose the route that works better. The other possibility is that factors outside of the repetition system determine the choice of repetition route. We formalize these two possibilities under three explicit hypotheses. These hypotheses identify plausible route recruitment mechanisms, but it should be noted that, because multiple mechanisms are certainly possible, the hypotheses are not mutually exclusive.

1 – The lexical-phonological hypothesis—This hypothesis states that the patients with weaker ability to access phonology from the lemma (i.e. lexical-phonological mapping; the lexical route) will support their repetition by adding the nonlexical route to the weak lexical route, thus repeating words as a dual-router. Patients with strong lexical-phonological mapping, however, would not need to invoke the nonlexical route. This hypothesis predicts that the strength of the model's P parameter should be positively correlated with the probability of being a lexical-router, as only patients with weak P's tend to add the nonlexical route.

2– The nonlexical hypothesis—This hypothesis asserts that patients with a weak nonlexical route will abandon that route in favor of the lexical route. If so, the strength of the model's NL parameter should be positively correlated with the probability of being a dual-router. Similarly, if the patient has difficulty holding the input string in their phonological working memory, mapping input phonemes to output phonemes – which is carried out by the nonlexical route - would be difficult (e.g. Baddeley, 1998; Gathercole et al., 1994; Gupta, 2003; Klein, Watkins, Zatorre, & Milner, 2006). Therefore, patients' scores on a measure of phonological working memory should correlate positively with the probability of recruiting the nonlexical route and being a dual-router.

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[2] Later on, we will provide an operational definition of what it means for one model to be "clearly superior." For now, we are using intuitive criteria.

3– The semantic-access hypothesis—This hypothesis proposes that patients who can access the meaning of a word try to repeat it through the lexical route, possibly because it is much more demanding to repeat it by mapping from the multiple components of the input (i.e. input phonemes) individually to multiple components of the output (i.e. output phonemes). This hypothesis, thus, predicts that a measure of semantic comprehension abilities would be positively correlated with the probability of being a lexical-router. Notice that the semantic-access hypothesis is claiming that the decision about whether to recruit the nonlexical route arises from assessment of a representation outside of the repetition system proper, namely the meaning of the word to be repeated.

The lexical-phonological and nonlexical hypotheses are examples of repetition-route recruitment criteria that depend on an assessment of the quality of the production system. Neurally, this translates to operations of the dorsal stream. The semantic-access hypothesis, on the other hand, highlights a mechanism through which a factor outside of the repetition system itself may determine which route is recruited. Neurally, this maps onto the influence of the ventral stream on operations in the dorsal stream. In what follows, we first use the methods described in Table 1 in a sample of 103 aphasic patients from the Moss registry to select patients who are clear lexical- and dual-routers. We then test the three hypotheses discussed above, and show that the data supports the semantic-access hypothesis, and to some extent, the nonlexical hypothesis. Finally, we report a meta-analysis of repetition route choice in patients from four previous studies, and demonstrate that our results are compatible with the past findings.

2. Moss Registry analysis

2.1. Methods

103 aphasic patients from Moss registry (www.mappd.org) who had completed the nonword repetition test were included in the study. All patients had completed the Moss aphasia battery, a subset of which is used in the current study.

2.1.1. Patient selection—Patient selection was done according to the 7 steps described in the introduction (see Table 1). Three test results were necessary for this procedure: picture naming, auditory word repetition, and auditory nonword repetition. Picture naming responses were obtained by administering the Philadelphia Naming Test (PNT; Roach et al., 1996). 175 normed line-drawings with high name agreement were shown to the patient, one at a time, with a 30-sec response deadline. Auditory word repetition scores were collected by having patients complete the Philadelphia Repetition Test (PRT), which uses the same items as the PNT, but instead of showing the pictures to the patients, the names are spoken to them, once only, and patients must repeat the names back to the experimenter. The Auditory nonword repetition test includes 60 of the PNT items turned into pronounceable nonwords, by changing two of their phonemes pseudo-randomly. Similar to the PRT, patients would hear the experimenter speak the nonword to them only once and must repeat them back.

For each patient, his/her actual repetition score (from the PRT) was compared to the two scores predicted by the lexical-route and the dual-route models. Then, we identified patients who would be excluded from the study because the model fitting did not clearly support one model over the other (i.e., an ambiguous case; see patient C in Table 1). Patients were excluded if one of the following two criteria were met:

> 1) if predictions of both models were far off from the patient's actual word repetition score. For example, if a patient only successfully repeats 50% of words spoken to him, but estimation of the lexical-route and dual-route models for this patient are 74% and

> 81% correct, respectively, it is evident that both models are doing a poor job in estimation. Thus, a comparison between the two models would be meaningless, and this patient should be excluded from the analysis. Formally, this was enforced by excluding all patients for whom the prediction of *both* models deviated from the patient's actual repetition score by 10% or more. Ten out of 103 patients were excluded after enforcing this criterion. Notice that this means that for over 90% of the patients, their word repetition accuracy was predicted within .10 by at least one of the repetition models.
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> 2) if the predictions of the two models were too close. For example, if the actual repetition was 78% correct, and the predictions of the lexical and dual route models were 76% and 81% correct, the two model's predictions differ by only 5%, and this difference is probably too small to be meaningful. Thus, a patient was excluded if s/he did not meet the formal criterion of a minimum difference of 10% or larger in model predictions (i.e. dual-route prediction– lexical-route prediction> 10%).

It is important to note that these criteria are somewhat arbitrary. We have simply attempted to set two theoretically-motivated criteria with a reasonable limit for exclusion. Importantly, we enforce the same criteria on two different samples (our large sample and the meta-analysis to follow). While there will inevitably be patients who are excluded by a close margin, the consistency gained by sticking to these formal criteria will help avoid cherry picking of cases and post-hoc exclusion of patients that may bias the results.

Thirty patients passed both of these criteria. For these patients, the difference between the actual word-repetition score and the predicted scores by the two models were compared. Whichever was lower, the patient was assigned to be better fitted by that model. This resulted in the identification of a contrastive sample of sixteen lexical-routers and fourteen dual-routers (Table 2). The rest of the patients were excluded because they could not be identified as a clear lexical- or dual-router. The majority of these patients belong in category C in Table 1, meaning that their repetition performance and prediction of both models are near ceiling. Theoretically, ambiguous patients may also belong to a different category: if the patient has very low NL weights, we would also expect predictions of the lexical-route and the dual-route models to be close. Note that for this to be true, the NL weight must be *very* low, because even small increases in NL cause notable differences between the predictions of the two models. As a rule of thumb, NL's associated with nonlexical repetition accuracy of 15% or more cause >10% difference between the lexical-route and the dual-route predictions. In our sample, there were only four patients who had nonlexical repetition lower than 15%. One of these patients was excluded by the first criterion (i.e. neither model was successful at reasonably estimating this patient's actual repetition score). The other three patients had repetition accuracy of 80%, 94% and 68%. Predictions of the lexical-route model for these patients were 76%, 89%, 63%, while the dual-route model predicted accuracy of 84%, 93% and 72%, respectively. All three seem to show some benefit of addition of the nonlexical route, even though this benefit is minor, not surprisingly, due to their small NL's. However, the small difference between the predictions of the lexical- and dual-route models for these patients does not allow us to categorize them into a clear group.

2.1.2. Comparing the lexical-routers and the dual-routers—Now that we have identified patients who are better fitted by one model vs. the other, we set out to test the differences between them. We build a logistic regression model, in which the repetition mode (lexical vs. dual) is predicted from a set of variables that address different aspects of production, comprehension, and memory processes potentially involved in the three hypotheses regarding route selection that we introduced earlier, the semantic access hypothesis, the lexical-phonological hypothesis, and the nonlexical hypothesis. The variables included in the model are described below:

- Square-root of P and NL: For the use in the regression models, parameters of the computational models were square-root transformed. The reason for this transformation is that differences between smaller parameter values represent larger differences in patients' abilities than differences between larger values. For example, when comparing a model with S=P=.010 to one with S=P=.015, the increase in weights of .005 decreases error rates by 23%; but the same weight increase from S=P=.030 to S=P=.035 will result in only 4% drop in error rates.

- Semantic-comprehension composite score: scores from three tests were combined to generate this composite score: the 52-item Pyramids and Palm Trees test (Howard and Patterson, 1992), the 64-item Camels and Cactus test (Bozeat et al., 2000), and a picture-name verification task based on the PNT. In the Pyramids and Palm Trees test, a pictured item must be matched to the closest associate among a set of two pictured choices on each trial (e.g., a picture of a pyramid must be matched to a picture of a palm tree or a picture of a pine tree). The Camels and Cactus test is similar in purpose, but has four same-category items to choose from and match to the target (e.g. if the target is ‘camel’, the choices would be between cactus, tree, sunflower or rose). The picture-name verification task uses the same pictures as the PNT, and the patient must pick the correct picture among semantic/phonological foils upon hearing a word. This measure did not exist for all patients in the registry. The scores on these three tests were normalized, and an average score was calculated to represent the semantic comprehension abilities.

- Synonym-judgment (noun variant; Saffran et al., 1988): In this 30-item task, the patient must decide, of the three spoken words, which two are most similar in meaning (e.g., violin, fiddle, clarinet). The reason that the scores of this task were entered separately – and not as a component of the semantic-comprehension composite – was that the task requires holding on to three items while making pairwise comparisons between them, which may pose a different demand on the cognitive system. Later on in the stepwise regression we show that this task explained a unique proportion of variance and was not redundant to the semantic-comprehension composite score.

- Lexical decision composite: To assess lexical retrieval abilities (with or without semantic access), scores on the word and nonword variants of the classic lexical decision task (Meyer & Schvaneveldt, 1971) were averaged to create a composite lexical decision score.

- Auditory discrimination composite score: Scores were averaged from the delayed and non-delayed versions of the phoneme discrimination task (N. Martin & Saffran, 1997). In the non-delayed version, the patient hears two items in immediate succession (20 lexical trials, and 20 nonlexical trials) and must judge whether the two were the same or different. Non-identical pairs differ in either onset or the final phoneme. The delayed version is very similar, except that the members of each pair are separated by a 5 second gap, during which the experimenter counts from 1 to 5. It is worth mentioning here that in our previous computational work (e.g. Nozari et al., 2010), we selected a sample of patients with “perfect recognition” (See Dell et al., 2007 for the formal criteria enforced). In the current study, we did not exclude patients based on their input processing abilities, and decided, instead to enter them in the model as a variable. However, the median score for the non-delayed version of auditory discrimination task in this sample was 93%, which implies that the majority of the patients studied here did, in fact, have good word recognition abilities.

- Short-term memory tests: Two measures of short-term memory were used, one to assess the maximum capacity of semantic short-term memory (category probe span; Freedman & R. Martin, 2001), and one to evaluate the maximum capacity of phonological short-term memory (rhyme probe test; based on Freedman & R. Martin, 2001). In the category probe span test, the patient listens to a string of *n* words, immediately followed by a target word, and then must determine if the final word is from the same semantic category as any of the preceding words by saying or pointing to 'Yes/No'. The *n* gradually increases and the test is terminated when accuracy drops to 75%. Performance yields the subject's maximum semantic short-term memory span. The main digit in scoring of this task represents the list in which the patient correctly recalled more than 50% of the items, and the decimal, the percentage of items correctly remembered in the list one level higher. For example, a score of 2.30 means that the patient recalled at least 50% of the items in a 2-word list, and 30% of the items in the 3-word list. In the rhyme probe test, the patient listens to a string consisting of *n* words, quickly followed by a target word, and must determine if the target word rhymed with any of the preceding words. Termination follows the same rule as in the test of semantic short-term memory. Although we expect the synonym judgment and delayed phoneme discrimination tasks to also tap into short-term memory processes, they assess the ability at a fixed demand level, while category and rhyme probe tasks provide us with the maximum capacity of these processes.

If the lexical-phonological hypothesis is right, one would expect stronger P weights to predict greater use of the lexical route. If the nonlexical hypothesis is correct, it should be the strength of the nonlexical route (NL), and/or the capacity of phonological working memory (rhyme probe scores) that predicts the recruitment of the nonlexical route. Finally, if the semantic-access hypothesis is right, we would expect higher semantic-comprehension composite scores to be predictive of more reliance on the lexical route. Four other scores were entered to account for other possibilities. Category probe scores and Synonym judgment scores both address semantic memory/executive processes, and lexical decision composite speaks to the ability to access lexical items, with or without access to semantics. Finally, Auditory discrimination composite score was entered to control for the deficits of input processing.

2.2. Results and discussion

A logistic regression model was built with all of the original predictors (Table 3): semantic-comprehension composite, lexical decision composite, auditory discrimination composite, synonym judgment, category and rhyme probe scores, and square-root transformed NL and P weights. In this full model, two variables had predictive power over the choice of route at $\alpha = .05$ significance level: better semantic-comprehension composite scores were associated with the choice of the lexical route only ($z = -2.1$, $p = .035$), and better rhyme probe scores predicted the recruitment of the nonlexical route ($z = 2.15$, $p = .031$)

To validate this finding we also sought the best fitting model to the data with the minimum number of variables. We ran a backward stepwise logistic regression model, in which the contribution of each variable to the model fit was assessed by comparing the log likelihood of the model against a nested model without that variable. We started with the full model, and at each step, the variable with the smallest contribution was removed, until the log-likelihood test no longer deemed any variable redundant. The final model consisted of the two variables that had been significant in the full model: semantic-comprehension (predicting lexical route repetition; $z = -1.94$, $p = .052$) and rhyme probe scores (predicting dual route; $z = 2.43$, $p = .01$). The synonym judgment scores were retained in the stepwise regression (higher scores predicting the dual route model), but its effect was nonsignificant, suggesting that it is a necessary variable for partitioning variance by the other two variables, without itself being a significant predictor of either repetition model.

These results support the semantic access hypothesis and the nonlexical hypothesis. When patients hear a word, choice of the repetition route is informed by 1) whether they can access the meaning of the word they heard (success inclines them toward use of the lexical route), and 2) their ability to hold phonemes in phonological working memory (good ability inclines toward use of the dual route).

The semantic access hypothesis is a reasonable account of how unimpaired speakers choose their repetition route (if you understand the word, you try to repeat it as a word you know). Our results suggest that patients also use this cue. This may be surprising, because in the case of patients, this cue may lead to the use of a route that does not function well. Given this, and the marginal p-value for the semantic-comprehension predictor in the regression that minimized the number of variables, it is important to replicate the semantic effect, and the absence of the predictive effect for parameters P and NL.

To this end, we next performed a meta-analysis of four earlier studies using similar methods that we reported above. These are all studies that assessed patient naming, and word and nonword repetition, and specifically used our computational methods to determine the patients' S, P, and NL parameters and to compare the lexical-route and dual- route repetition models. We took these patients, and identified lexical-routers and dual-routers among them using the same criteria as before, and tested the semantic access hypothesis as an account of the differences between the groups. But since these studies do not report the ancillary test scores that we used here for semantic comprehension (and some of them report no comprehension scores), we needed to find an indirect way of measuring this in these patients. Our solution, as described below, is to use the model-derived S weights, which are reported for all of the patients in the studies comprising the meta-analysis, as a proxy for semantic comprehension. As before, we will also examine the P and NL weights. Thus, we will be comparing how the S, P, and NL weights predict membership in the lexical-router and dual-router groups.

Using S weight as a proxy for semantic comprehension requires justification, as technically, the S weight is estimated from picture naming, a production task. We provide a threefold justification. First, as we noted above, Dell et al. (2013) have recently shown a clean distinction between the mapping of S and P weights to ventral and dorsal streams. The association of the S weight with temporal regions in the ventral stream suggests that its value correlates with semantic comprehension abilities. Second, previous research has quantitatively demonstrated that the model estimated S weights correlate strongly with semantic comprehension abilities. Hanley and Nickels (2009) reasoned that production and comprehension abilities tend to use common semantic resources, but distinct phonological resources (e.g. see also Warker, Xu, Dell, & Fisher, 2009). They evaluated 19 patients' picture naming estimating the model-derived S and P weights, and then correlated these weights with independently derived measures of semantic and phonological input processing. It turned out that S weight correlated well with semantic input processing measures, but P weight did not correlate with measures of phonological input processing. For our purposes, the key result is that S weight can function as an indirect measure of semantic comprehension. As a final justification for using S weight to measure comprehension, we replicate Hanley and Nickel's study using our much larger original sample. While Hanley and Nickels (2009) tested a smaller sample, we used the 103 patients in our original sample. Table 4a shows the correlations between the strength of the S parameter and our semantic and lexical comprehension tests. All these correlations were positive and reliable, after correction for multiple comparisons (Table 4a; See also Nickels & Howard, 1994; but see N. Martin & Saffran, 2002). Also, as predicted, Parameter P did not show a reliable correlation with measures of input processing (see also Howard & Nickels, 2005; Martin, 2003; Nickels & Howard, 1995). Although positive, none of the correlations involving P reached significance after correction for multiple comparisons (Table 4b). These results support a close relationship between comprehension and production at the lexical-semantic mapping (although not further down in the system), and validate our assumption that S weights can be a useful measure of semantic comprehension.

In summary, we claim that S weight should provide an indirect, but useful index of semantic access. If so, and if the semantic access hypothesis is true, lexical-routers should have stronger S weights.

3. Meta-analysis

3.1. Methods

A total of 82 phasic patients reported in four studies (Abel et al., 2009; Baron et al., 2008; Dell et al., 2007; Hanley et al., 2004) were surveyed. The studies used different production tests: Abel et al. (2009) used 160 line drawings from Snodgrass and Vanderwart (1980) for picture naming, and a subset of those pictures (n = 40) for auditory word repetition. For nonword repetition, 40 one-syllable nonwords from the LeMo battery (De Bleser, Cholewa, Stadie, and Tabatabaie, 2004) were used. Baron et al. (2008) used 210 line-drawings administered over three sessions (70 items/session) with a short (10 second) response deadline for each item. The same items were used in the auditory word repetition task. For auditory nonword repetition, 80 nonwords from the PALPA 9 nonword repetition test were used. Dell et al., (2007) used the 175-item Philadelphia Picture Naming (PNT) test with a 30-second deadline to assess naming. The same items were administered to assess auditory word repetition, and a 60-item nonword repetition was used to evaluate patients' ability to repeat nonwords (see the *Moss Registry Analysis* section of this paper for more details on these tests). Finally, Hanley et al. (2004) used 40 pictures from test 53 of the PALPA battery (Kay, Lesser, & Coltheart, 1996) for picture naming, the same items for auditory word repetition, and 80 nonwords from PALPA 9 were used to test patients' ability to repeat nonwords (the nonword test information was retrieved from the original study of the two patients in Hanley et al., 2002).

3.1.1. Patient selection—The same method was used as described in the previous section. The same criteria were imposed on the data for selecting lexical- and dual-routers. This process resulted in identifying a contrastive sample of eight lexical-routers and twelve dual-routers (Table 5).

2.1.2. Comparing the lexical-routers and the dual-routers—Three planned comparisons were made between the two groups, corresponding to the three hypotheses of the study tested on the large sample earlier. The strength of the S weights (as a test of the semantic-access hypothesis), the strength of the P weights (as a test of the lexical-phonological hypothesis), and the strength of the NL weights (as a test of the nonlexical hypothesis) were compared between the two groups using a t-test. For all three comparisons, in keeping with the earlier analyses, square-root transformed variables were used.

3.2. Results and Discussion

Once the selection process was completed, the parameters of the naming model were compared between the two groups (Fig. 2). The P parameter did not differ significantly between the lexical-and the dual-routers (.016, SE = .002 for the lexical-routers and .017, SE = .002 for the dual-routers; $t(1,18) = .68$, $p = .57$), and neither did the NL parameter (.031, SE = .003 for the lexical-routers and .040, SE = .005 for the dual-routers; $t(1,18) = 1.09$, $p = .29$). These results are consistent with the results of our large-sample analysis. The S parameter, on the other hand, was significantly larger in the lexical- than the dual-routers (.

022, SE = .002 for the lexical-routers and .014, SE = .003 for the dual-routers (t(1,16.8) = 2.36, p = .03). These findings clearly support the semantic access hypothesis and are contrary to the lexical-phonological hypothesis. Thus, as in the previous study, using the lexical route alone characterizes patients with good semantic comprehension. This conclusion, as we noted, requires the assumption that S weight is associated with semantic comprehension.

5. General Discussion

Much research has been concerned with aphasic auditory word repetition, and the cognitive and neural mechanisms behind it. The fruit of this research has been the introduction of two cognitive models, the lexical-route and the dual-route models. While the former bases word repetition entirely on recognition and activation of the existing lexicon, the latter recruits a nonlexical route, which directly maps input to input phonology. More recently, additional support for the dual-route approach has been provided by demonstrating its neural correlates (Dell et al. in press; see also Das, Padakannaya, Pugh, & Singh, 2011 for neural correlates of a dual-route model of reading). Although we have based our work on the implemented dual-route model of Nozari et al. (2010), we note that most models of impaired auditory repetition use dual-route architectures (see Hanley et al., 2002, for review). This includes models that are strongly interactive and distributed, such as that of Ueno et al. (2011), which has two routes, with one route considerably more sensitive to lexical information than the other.

The main question of this study was which factors determine whether the lexical route is used alone or whether the nonlexical route is recruited. Observing repetition performance after brain damage provides an opportunity to answer this question. Some aphasic patients recruit the nonlexical route for repetition, while others rely solely on their lexical routes (e.g. Dell et al., 2007; Hanley et al., 2002; Nozari et al., 2010). It is noteworthy that beyond aphasic production, auditory repetition in neurologically healthy adult speakers is highly likely to exhibit variability in whether or not the nonlexical route is recruited. This variability, however, reflects the nature of the verbal stimulus, rather than brain damage. The nonlexical route is recruited when the item to be repeated is not part of the person's lexicon (as in learning a new language, or when the word is simply not known), and as such cannot be looked up in the production system (See also Budd, Hanley, & Nozari, 2012, for a report on the differential use of lexical-route and dual-route models innormally-developing children of different age groups).

We reported two analyses, one on a large sample of 103 patients (the main study), and the other a meta-analysis of four earlier studies, in which we singled out patients who were distinctly better fits to the lexical-route or the dual-route models, and compared them under three hypotheses. The lexical-phonological hypothesis and the nonlexical hypothesis both predicted that the quality of the repetition routes would predict whether they are used, or the degree to which they are relied upon. Specifically, the lexical-phonological hypothesis predicted that stronger P weights should entail better fits for the lexical-route model, and the nonlexical hypothesis posited that stronger NL weights should predict better fits for the dual-route model. Neither of these was confirmed in either sample.

The nonlexical hypothesis had a second prediction as well: it might not be the quality of the system mapping the input to output phonology, but the capacity of phonological working memory, which is essential for holding the input phonemes in mind while mapping them to output phonemes, that would determine whether the nonlexical route is recruited. If so, higher scores on a rhyme probe task should be associated with higher probabilities of being a dual-router. This prediction was supported in the main analysis (these scores were not available for the patients in the meta-analysis). Finally, the third hypothesis, the semantic-access hypothesis, stated that if the word's meaning can be accessed, the speaker will rely on the lexical route for repetition. This prediction was confirmed, in both the main study by showing that higher semantic-comprehension scores were associated with higher probability of being a lexical-router, and in the meta-analysis by showing that the lexical-routers had significantly higher S weights, as a proxy for semantic comprehension. Additional support for the semantic-access hypothesis comes from auditory repetition in patients with semantic dementia. Jefferies, Crisp, and Lambon-Ralph (2006) showed that, compared to a group of patients with phonological but not semantic impairments, patients with semantic dementia demonstrated a diminished effect of lexicality and imageability in repetition, compatible with recruitment of the nonlexical route.

In summary, we found support for the semantic-access hypothesis, partial support for the nonlexical hypothesis, and no support for the lexical-phonological hypothesis. One way to integrate these findings is to distinguish between route choice factors that are *within* the repetition systems, and those that are *outside* the repetition system. The lexical-phonological and the nonlexical hypotheses refer to within-repetition factors. Cognitively, parameters P and NL are core parameters of the lexical and nonlexical repetition routes, respectively. Neurally, too, P and NL map neatly to the dorsal stream, and correspond to the same brain regions identified in auditory word repetition (Dell et al., 2013). On the other hand, parameter S, which corresponds closely to semantic-lexical retrieval, is neither cognitively, nor neurally within the boundaries of repetition. The fact that the semantic-access hypothesis is supported, thus, is quite interesting in showing that factors outside of the repetition system itself influence how repetition is carried out. Neurally-speaking, this is an indirect demonstration of the influence of the ventral stream over the dorsal stream.

We did, however, find partial support for the nonlexical hypothesis: higher rhyme probe scores, but not stronger NL weights, were associated with deployment of the nonlexical route. We think this contrast (rhyme-probe, not NL, predicting the use of the nonlexical route) fits well with our other finding that successful semantic access inclines toward the lexical route. To show this point, we regroup the results in a different way. If the choice of the repetition route is viewed as an implicit metacognitive judgment that is based on cues, some cues will be easier to use than others. The cue of whether the stimulus is meaningful or not is an easy one to use. If meaning is accessed, then the item is a meaningful word. Similarly, it is easy to know whether one remembers the item to be repeated, or has already forgotten it. These judgments can be made on the spot, and do not require consultation of past successes of failures. Our results suggest that such on-the-spot cues are in fact the ones used for repetition route recruitment: Recognizing meaning biases for lexical route repetition, but good phonological memory of the item biases for recruiting the nonlexical route. The intactness of lexical-route (parameter P) or nonlexical route (parameter NL) does not seem to matter, because the qualities of these routes, as relevant as they may be as cues, are not accessible on the spot. For example, the only way to know that one's lexical-phonological mapping (i.e. parameter P) is weak is to recall that past attempts at assembling the phonology of a known word have failed.

In summary, our results suggest that upon hearing a word, people use certain cues to activate the repetition route. The cognitive ease with which these cues are accessed determines which ones are used for repetition route selection. Access to meaning is an available cue and promotes reliance on the lexical route. The ability to remember the words phonology is another easily-accessible cue, and promotes the addition of the nonlexical route. Among patients, this also reflects adherence to a strategy successfully used in the past. In neurologically healthy individuals, when the word is known, lexical route is the less effortful repetition route. If, however, access to meaning fails, the person will attempt to recruit the nonlexical route. Successful recruitment of this route is, of course, contingent on the person's ability to hold the input string in phonological memory long enough for it to be mapped on to the output phonology. If this step fails, due to limitations in the capacity of phonological working memory, the nonlexical route is abandoned.

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Two groups of lexical- and dual-routers for auditory repetition were identified.

Lexical-routers had better comprehension, but not better phonological production.
This was demonstrated in a large-group analysis and a meta-analysis of 4 studies.
Dual-routers had better phonological working memory.

We conclude that ventral and dorsal streams interact for auditory word repetition.

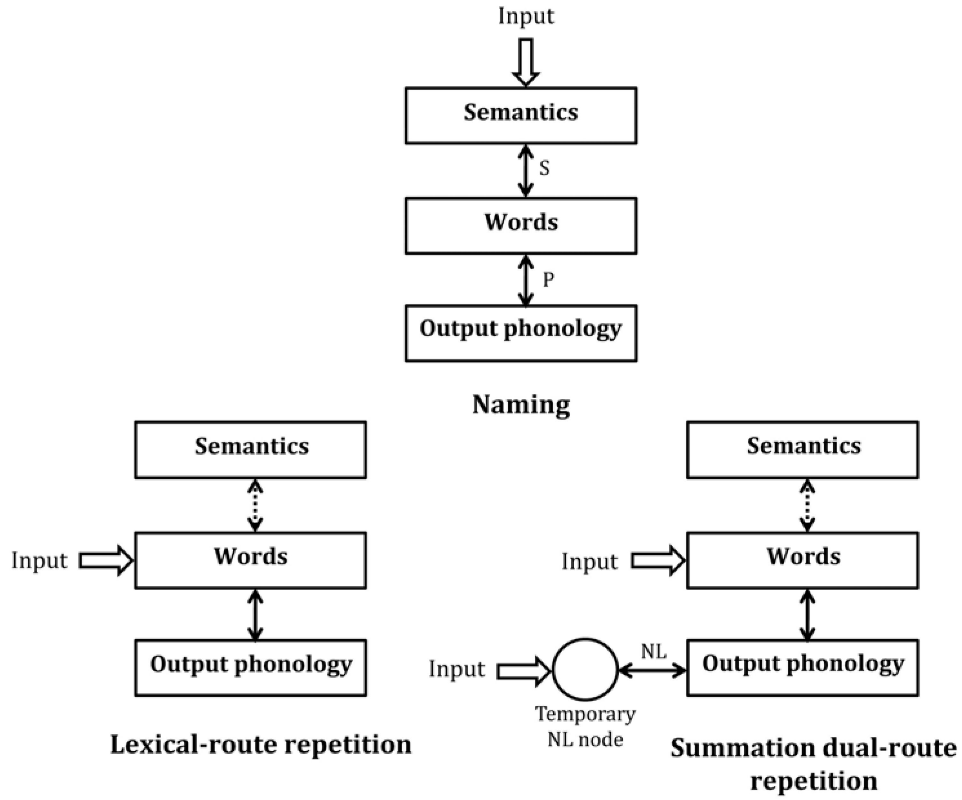

Fig. 1.

Schemata of the naming model (upper panel), the lexical-route, and the dual-route repetition models (lower panel). “Input” represents the jolt that simulates perfect auditory word recognition. Dashed arrows indicate that semantic representations are only indirectly involved in repetition.

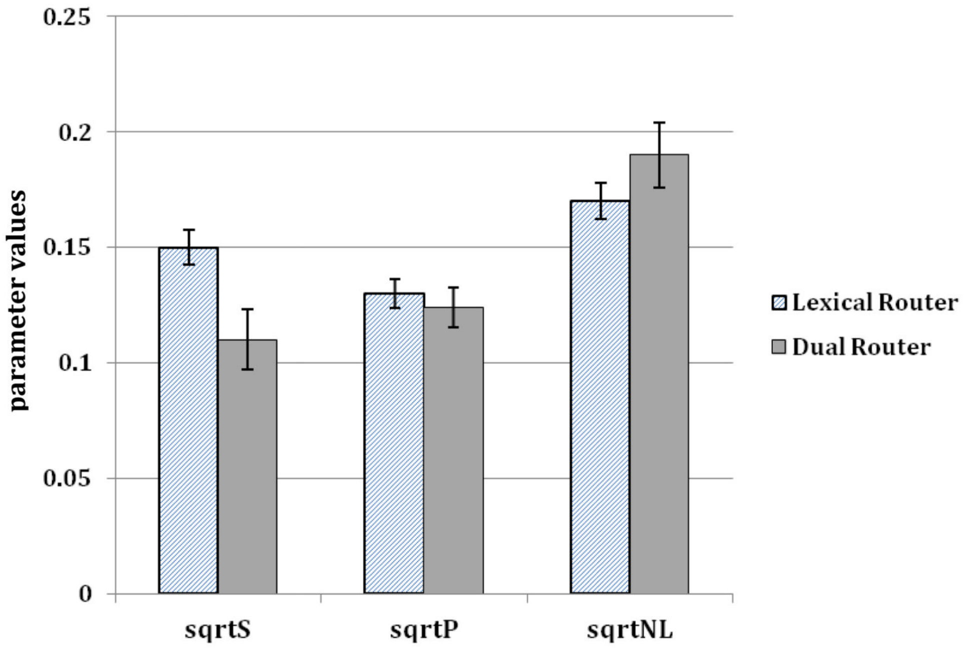

Fig. 2.

Average square-root transformed S and P parameters in the lexical- and dual-routers in the meta-analysis. Error bars represent the 2SE of the mean. sqrtS = square-root of S; sqrtP = square-root of P.

Table 1

Selection of model parameters and determination of best word-repetition model for three example patients

a. Obtain patient naming error pattern on the Philadelphia Naming Test (PNT).

Patient	Correct	Semantic error	Phonological error	Mixed error	Unrelated error	Nonword error
Patient A	.49	.07	.04	.05	.04	.30
Patient B	.29	.02	.20	.01	.04	.45
Patient C	.90	.05	0	.02	.01	.02

b. Fit model to naming response proportions to obtain S and P parameters. Table shows predicted proportions for the closest fit of the model to the empirical data from each patient (Compare model values to data in a). rmsd = root mean square deviation.

Patient	Correct	Semantic error	Phonological error	Mixed error	Unrelated error	Nonword error
Patient A S = .020, P = .016, rmsd = .03	.52	.07	.08	.02	.04	.26
Patient B S = .019, P = .009, rmsd = .05	.26	.05	.10	.02	.05	.52
Patient C S = .028, P = .028, rmsd = .008	.89	.05	.02	.01	0	.03

c. Obtain patient response proportions in nonword auditory repetition test.

Patient	Correct response	Lexicalization errors	Nonword errors
Patient A	.37	.33	.30
Patient B	.37	.22	.41
Patient C	.85	.13	.02

d. Using model set up with the fitted values of S and P for each patient; determine the best value of NL so as to match nonword repetition performance. Table shows predicted proportions for the closest fit of the model to the empirical data from each patient (Compare model values to c)

Patient	Correct response	Lexicalization errors	Nonword errors
Patient A nl = .026, rmsd = .094	.36	.22	.42
Patient B nl = .026, rmsd = .014	.36	.21	.43
Patient C nl = .051, rmsd = .037	.86	.08	.06

e. Using model parameters S, P, and NL, predict performance in a word repetition test from the dual-route Repetition Model.

Patient	Correct	Semantic error	Phonological error	Mixed error	Unrelated error	Nonword error
Patient A	.91	0	.02	0	0	.07
Patient B	.75	0	.05	0	0	.19
Patient C	1.00	0	0	0	0	0

f. Using model parameters S and P, predict performance in a word repetition test from the lexical-route Repetition Model (i.e. NL = 0)

Patient	Correct	Semantic error	Phonological error	Mixed error	Unrelated error	Nonword error
Patient A	.65	0	.07	.01	0	.27
Patient B	.34	0	.10	.01	.01	.53
Patient C	.96	0	.01	0	0	.03

g. Obtain performance on a word repetition test (Philadelphia Repetition Test) for the patients to compare to model predictions (e and f). Determine which repetition model had the best predictions.

Patient	Correct	Semantic error	Phonological error	Mixed error	Unrelated error	Nonword error
Patient A	.95	0	.01	0	0	.04
Patient B	.39	0	.13	0	.01	.46
Patient C	.97	0	.02	0	0	.01

Table 2

Word repetition scores, as well as predictions of the lexical and dual-route repetition models for the lexical- and dual-routers selected from the 103 patients in the Moss database. Lexical dev = Word repetition score − Lexical-route model's prediction. Dual dev = Word repetition score − Dual-route model's prediction.

Patient	Word Repetition	Lexical Model	Dual Model	Lexical Dev	Dual Dev	Category
1	67	75	89	−8	−22	Lexical
2	70	75	91	−5	−21	Lexical
3	81	86	96	−5	−15	Lexical
4	75	78	91	−3	−16	Lexical
5	57	59	81	−2	−24	Lexical
6	76	78	92	−2	−16	Lexical
7	74	75	93	−1	−19	Lexical
8	88	88	98	0	−10	Lexical
9	86	85	97	1	−11	Lexical
10	85	83	96	2	−11	Lexical
11	79	76	93	3	−14	Lexical
12	85	81	95	4	−10	Lexical
13	87	83	97	4	−10	Lexical
14	86	81	94	5	−8	Lexical
15	42	35	59	7	−17	Lexical
16	58	50	78	8	−20	Lexical
17	92	85	95	7	−3	Dual
18	97	90	100	7	−3	Dual
19	96	88	98	8	−2	Dual
20	96	88	100	8	−4	Dual
21	90	79	96	11	−6	Dual
22	74	61	79	13	−5	Dual
23	97	84	96	13	1	Dual
24	97	84	99	13	−2	Dual
25	71	57	76	14	−5	Dual
26	81	67	84	14	−3	Dual
27	75	61	83	14	−8	Dual

Patient	Word Repetition	Lexical Model	Dual Model	Lexical Dev	Dual Dev	Category
28	94	79	98	15	−4	Dual
29	87	60	94	27	−7	Dual
30	89	50	90	39	−1	Dual

Table 3

Variables entered into the logistic regression model for comparing lexical- and dual-routers. L = Lexical, D = Dual, Catprobe = category probe score, Rhyprobe = rhyme probe score, LDcomp = lexical decision composite score, Audcomp = auditory discrimination composite score, sqrtP = square-root transformed P parameter, sqrtNl = square-root transformed NL parameter, Sem-Comp = semantic-comprehension composite score, SynNoun = synonym judgment (noun variant) score.

Patient	Router	Catprobe	RhyProbe	LDcomp	Audcomp	sqrtP	sqrtNL	Sem-Comp	SynNoun
1	**L**	0.5	1	79	50.50	.122	.130	79.67	73
2	**L**	0.5	1.53	93	83.00	.140	.141	69.00	60
3	**L**	1	2	82	78.00	.157	.145	79.00	73
4	**L**	2.35	2	91	94.00	.134	.130	90.00	87
5	**L**	2.15	3	91	89.00	.107	.130	83.00	80
6	**L**	2.54	1.3	83	94.00	.121	.138	88.33	63
7	**L**	0.5	1.21	83	80.50	.143	.145	76.33	93
8	**L**	1.75	1.8	80	89.00	.141	.176	91.67	93
9	**L**	2.45	4	93	92.50	.117	.173	92.67	67
10	**L**	0.5	1.35	87	92.50	.145	.148	77.00	80
11	**L**	1.5	1.57	85	84.00	.126	.148	87.67	73
12	**L**	2.47	2.56	91	90.50	.124	.155	96.33	100
13	**L**	2.8	0.5	84	82.50	.145	.161	86.67	100
14	**L**	3	1	91	71.50	.152	.145	84.00	100
15	**L**	1.64	0.5	79	79.00	.102	.118	75.33	60
16	**L**	2	0.5	84	72.50	.118	.138	56.00	60
17	**D**	0.5	1.6	86	50.50	.151	.141	43.67	47
18	**D**	2	5.2	96	97.50	.148	.202	91.00	100
19	**D**	4.44	3.67	91	90.50	.138	.176	95.67	100
20	**D**	1.75	3.4	94	88.00	.152	.221	87.33	93
21	**D**	3	1.82	94	95.00	.122	.170	95.00	100
22	**D**	2.1	1.6	73	75.50	.122	.118	91.50	93
23	**D**	2	3	94	86.50	.143	.155	89.67	87
24	**D**	2	3.81	97	90.00	.146	.197	89.00	100
25	**D**	2	3	93	89.00	.106	.114	86.33	87
26	**D**	1.33	1.17	*77*	81.50	.129	.118	81.33	93

Patient	Router	Catprobe	RhyProbe	LDcomp	Audcomp	sqrtP	sqrtNL	Sem-Comp	SynNoun
27	**D**	3.0	3.44	88	94.00	.122	.130	87.50	100
28	**D**	2.17	4	95	88.00	.131	.190	90.67	100
29	**D**	4	6.6	92	94.00	.125	.182	96.33	100
30	**D**	0.5	0.5	85	79.00	.119	.176	56.33	40

Table 4

(a) Pearson correlations (and the relevant p values) between the strength of the S parameter (as an index of lexical-semantic processing in production) and various lexical and semantic comprehension scores, in a sample of 103 aphasic patients. Reported P values are corrected for the number of tests and are comparable to α = 0.05. (b) Pearson correlations (and their relevant p values) between the strength of the P parameter (as an index of lexical-phonological processing in production) and various input processing measures, in a sample of 103 aphasic patients. Reported P values are corrected for the number of tests and are comparable to α = 0.05.

(a)

	Pyramids & Palm Trees	**Camels & Cactus**	**Synonym Judgment**	**Lexical Decision (words)**	**Lexical Decision (Nonwords)**
Pearson's r	.50	.61	.50	.32	.29
P value	<.001	<.001	<.001	.005	.015

(b)

	Auditory Discrimination (Non-delayed)	**Lexical Decision(words)**	**Lexical Decision (Nonwords)**
Pearson's r	.19	.17	.2
P value	.18	.27	.12

Table 5

Meta-analysis of the lexical- and dual-routers. Repetition accuracy and models predictions are in percentages. Lexical dev = Word repetition score − Lexical-route models prediction. Dual dev = Word repetition score − Dual-route model's prediction. S and P are model parameters (See text).

Patient	Word Repetition	Lexical model	Dual model	Lexical dev	Dual dev	Router	S	p	NL
M1	0.97	0.65	0.97	0.32	0	DUAL	0.005	0.017	0.04
M2	0.9	0.75	1	0.15	0.1	DUAL	0.019	0.018	0.08
M3	0.27	0.06	0.27	0.21	0	DUAL	0.001	0.001	0.018
M4	0.83	0.64	0.76	0.19	−0.07	DUAL	0.019	0.015	0.009
M5	0.95	0.8	0.97	0.15	0.02	DUAL	0.014	0.021	0.033
M6	0.9	0.61	0.96	0.29	0.06	DUAL	0.002	0.017	0.04
M7	0.95	0.65	0.91	0.3	−0.04	DUAL	0.02	0.016	0.026
M8	0.95	0.8	0.99	0.15	0.04	DUAL	0.024	0.019	0.045
M9	0.92	0.61	0.97	0.31	0.05	DUAL	0.021	0.014	0.044
M10	0.98	0.85	1	0.13	0.02	DUAL	0.027	0.02	0.056
M11	0.97	0.67	0.98	0.3	0.01	DUAL	0.005	0.018	0.046
M12	0.91	0.76	0.98	0.15	0.07	DUAL	0.017	0.019	0.039
M13	0.81	0.78	0.96	0.03	0.15	LEXICAL	0.028	0.017	0.03
M14	0.7	0.79	0.95	−0.09	0.25	LEXICAL	0.017	0.020	0.025
M15	0.67	0.66	0.86	0.01	0.19	LEXICAL	0.017	0.016	0.018
M16	0.39	0.34	0.75	0.05	0.36	LEXICAL	0.019	0.009	0.026
M17	0.9	0.84	0.99	0.06	0.09	LEXICAL	0.022	0.021	0.041
M18	0.78	0.83	0.98	−0.05	0.2	LEXICAL	0.015	0.023	0.034
M19	0.9	0.84	0.98	0.06	0.08	LEXICAL	0.027	0.02	0.036
M20	0.88	0.79	0.98	0.09	0.1	LEXICAL	0.034	0.016	0.035