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Selective short-term memory deficits arise from impaired domain-general
semantic control mechanisms

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Running head: Short-term memory and semantic control

Abstract

Semantic short-term memory (STM) patients have a reduced ability to retain semantic information over brief delays but perform well on other semantic tasks, suggesting damage to a dedicated buffer for semantic information. Alternatively, their difficulties may arise from mild disruption to domain-general semantic processes that have their greatest impact on demanding STM tasks. In this study, we demonstrated mild semantic processing impairments in two semantic STM patients. They performed well on untimed semantic tasks but were deficient in accuracy and reaction times on speeded tasks. Demanding semantic production tasks were also affected. They were compared with a case-series of individuals with semantic aphasia – multi-modal semantic difficulties stemming from poor cognitive control. STM and semantic performance were more impaired in this group but there were qualitative similarities to the semantic STM cases. The difference between the two patient types may be one of degree. In semantic aphasia, severe disruption to semantic control leads to global semantic impairments while milder disruption in semantic STM cases might impact mainly on STM tests because of the high control demands of these tasks.

Keywords: short-term memory, stroke aphasia, semantic control

Introduction

Models of verbal short-term memory (STM) have traditionally emphasised the importance of phonology in list recall (e.g., Baddeley & Hitch, 1974) but more recent research has established a role for lexical and semantic knowledge in repetition tasks (Bourassa & Besner, 1994; Hulme, Maughan, & Brown, 1991; Hulme et al., 1997; Jefferies, Frankish, & Lambon Ralph, 2006; Poirier & Saint-Aubin, 1995; Walker & Hulme, 1999). Neuropsychological studies have a bearing on this issue, with semantic memory impairments in semantic dementia (SD) and stroke aphasia associated with particular STM deficits (Berthier, 2001; Jefferies, Hoffman, Jones, & Lambon Ralph, 2008; Jefferies, Jones, Bateman, & Lambon Ralph, 2004; Knott, Patterson, & Hodges, 1997, 2000; Majerus, Norris, & Patterson, 2007; Martin & Ayala, 2004; Martin & Saffran, 1990; Martin & Saffran, 1997; McCarthy & Warrington, 1987, 2001; Patterson, Graham, & Hodges, 1994). A key feature in both of these groups is a reduction or abolition of the normal effect of “lexicality” – the advantage healthy subjects receive when repeating word lists relative to lists of nonwords as a result of lexical-semantic knowledge (Hulme et al., 1991). This is line with the idea that lexical-semantic contributions to STM are disrupted in patients with impaired semantic memory (Patterson et al., 1994). Intriguingly, there are a handful of stroke patients reported who show a reduced lexicality effect, and other difficulties in retaining semantic information over time, but perform well on other semantic tasks (Freedman & Martin, 2001; Martin & He, 2004; Martin & Lesch, 1996; Martin, Shelton, & Yaffee, 1994). This pattern has been termed a “semantic STM deficit” because the lexical-semantic aspects of STM are selectively impaired while long-term semantic knowledge appears relatively preserved. The nature of this unusual deficit, and its relation to other semantic disorders, are the focus of this study.

Martin, Shelton and Yaffee (1994) first reported a case with a semantic STM deficit. Patient AB showed no lexicality effect, indicating a problem with lexical-semantic aspects of

STM. In contrast, his recall was sensitive to word length and phonological similarity, both indicators of normal phonological retention (Baddeley, Thompson, & Buchanan, 1975; Conrad, 1964; Conrad & Hull, 1964). AB scored within the normal range on tests of picture naming and single-word comprehension, suggesting that semantic processing more generally was spared. The performance of this patient was contrasted with another case, EA, who had deficits in phonological retention. She showed no effects of word length or phonological similarity in her immediate serial recall and recalled lists of nonwords much more poorly than real words. The differences between the two patients were exemplified by their performance on two tasks that explicitly tapped either phonological or semantic storage. In a rhyme probe task, patients heard a list of words and verified whether a probe rhymed with any of them. In a category probe task, patients heard a list of words and verified whether a subsequent probe belonged to the same semantic category as any of them. The two tasks therefore emphasised retention of either the phonological or semantic characteristics of the list items respectively. Although the patients showed abnormal performance on both tasks, AB was more impaired on the category than the rhyme task while EA showed the reverse dissociation. Later, an additional patient ML was reported who presented a similar semantic STM deficit to AB (Martin & He, 2004; Martin & Lesch, 1996). ML's ability to name pictures and comprehend single words was also good.

Martin and colleagues attributed the deficit in AB and ML to the disruption of a STM store specialised for the retention of lexical-semantic information (Martin, Lesch, & Bartha, 1999; Martin et al., 1994). This multi-component model of STM explains the dissociation between lexical-semantic STM impairment and phonological STM impairment, which forms the major focus of existing research into semantic STM cases. By positing a separate system for short-term retention of semantic information that is independent of the mechanisms underlying performance on other semantic tasks, the account also fits the apparently selective

deficits to STM in these patients. However, an alternative perspective, and one that has not been previously explored in detail, is that semantic STM deficits are a consequence of disruption to more general semantic processes. On this view, semantic STM patients *do* have general deficits of semantic processing, albeit rather subtle ones that may not be detected on standard semantic tasks. The impact of this mild semantic impairment is observed on semantic STM tasks and not on tests of phonological STM (or on most single-word semantic tasks) simply because semantic STM tasks place the greatest demands on the semantic system. On this view, impairment would be expected on other semantic tasks that were sufficiently demanding, irrespective of their STM load.

There are some hints that semantic STM patients have difficulty with demanding tasks that do not load heavily on STM. Patient AB was error-prone when verifying whether a word belonged to a particular semantic category but only when the stimuli were presented for a limited time period (Martin et al., 1994). His reaction times were also slower than those of controls on this and on other speeded comprehension tests (living/non-living judgements and verification of property statements such as “belt has buckle”). Patient ML showed slow response times on the category verification task (Martin & He, 2004). In the present study, we explored in two new semantic STM cases the hypothesis that the semantic STM profile is the consequence of a mild general semantic impairment. Rather than focusing on the dissociation between semantic and phonological STM impairments, we compared our semantic STM patients to a case-series of stroke aphasics with multi-modal semantic deficits, to determine to what extent a similar underlying impairment could account for both sets of symptoms. To put our investigation into context, it is important that we address at the outset the following key question: why would we expect a mild semantic impairment to affect semantic STM tasks to a greater extent than other semantic tasks? This requires a departure from the domain of STM to consider how the semantic system itself is organised.

Disorders of semantic representation vs. semantic control

Disorders of comprehension are present in a number of conditions and their precise form can be rather variable. Some patients have modality-specific comprehension impairments (e.g., pure word deafness) that can be attributed to pre-semantic levels of processing. In other cases, semantic processing is impaired across a range of input and output modalities, implicating damage to a central semantic system. These multi-modal semantic impairments are most commonly associated with SD, a neurodegenerative condition in which core semantic knowledge degrades progressively in a very selective manner (Hodges, Patterson, Oxbury, & Funnell, 1992; Rogers et al., 2004; Snowden, Goulding, & Neary, 1989). Comprehension impairments affecting both verbal and non-verbal modalities can also occur in stroke aphasia (Chertkow, Bub, Deaudon, & Whitehead, 1997; De Renzi, Faglioni, Scotti, & Spinnler, 1972; Gainotti, Miceli, & Caltagirone, 1979; Gainotti, Silveri, Villa, & Caltagirone, 1983; Hart & Gordon, 1990; Saygin, Dick, Wilson, Dronkers, & Bates, 2003; Spinnler & Vignolo, 1966) and as a convenient shorthand, we will refer to the impairment in these stroke cases as semantic aphasia (SA).¹ Despite the apparent symptom overlap between SD and SA, distinct brain regions are involved in each condition. In SD, atrophy and hypometabolism are centred bilaterally on the anterior temporal lobes (Mummery et al., 2000; Nestor, Fryer, & Hodges, 2006). In contrast, semantic impairments in stroke aphasia have been associated with frontal and temporoparietal infarcts (e.g., Berthier, 2001; Chertkow et al., 1997).

A recent study used a case-series methodology to compare semantic performance in SD and SA directly (Jefferies & Lambon Ralph, 2006). Although the two groups showed similar overall levels of impairment, qualitative differences emerged. The SD patients

¹This term is not intended to exclude the possibility that individual patients of this sort may have additional non-semantic deficits.

showed substantial consistency when the same set of items was assessed across different semantic tests. They were also highly sensitive to frequency in a range of tasks. These findings are consistent with the view that SD patients suffer degradation of a store of amodal semantic representations (Patterson, Nestor, & Rogers, 2007; Rogers et al., 2004). The SA patients, in contrast, did not perform consistently on tasks that required different types of semantic judgement (e.g., simple matching tasks vs. judgements of semantic association) even when the same concepts were probed, suggesting that their deficits did not stem from loss of the knowledge store itself. They often succeeded in retrieving the semantic information required for one task, but then were unable to reshape the information to meet the requirements of another task. In contrast to the SD cases, they were not sensitive to item frequency. Further investigations revealed that, unlike SD patients, SA cases showed “refractory” effects in semantic tasks: performance deteriorated when a small set of semantically related items was presented several times (Jefferies, Baker, Doran, & Lambon Ralph, 2007; see also Warrington & Cipolotti, 1996). These characteristics have been associated with impaired *access* to semantic information rather than damage to the semantic store itself (Warrington & McCarthy, 1983; Warrington & Shallice, 1979).

These contrasting patterns of performance were consistent with the hypothesis that semantic cognition consists of two interactive components: (1) amodal semantic representations that code our knowledge of concepts and their inter-relationships and (2) control processes that access and manipulate these representations to achieve appropriate semantically-driven behaviour. In SD, semantic representations in the anterior temporal lobes degrade and are no longer available to drive semantic performance. Since the same representations are required irrespective of the precise nature of the task, this leads to a high level of consistency between different tasks. However, intact semantic representations alone cannot drive appropriate semantic behaviour. We know many things about objects and only a

small subset of this vast store of information is relevant at any given time. To borrow an example from Saffran (2000), if asked to play a piano it is necessary to access information about the functions of the keys and the pedals. But if our task is to move the piano across the room, a different set of piano-related features becomes relevant: it is now important to know that pianos are heavy and that they usually move on wheels. Our view is that *semantic control* processes allow us to access and manipulate semantic knowledge in a flexible and task-appropriate manner, ensuring that the relevant aspects of knowledge are processed and irrelevant ones ignored. An impairment of this function can explain the pattern of deficits seen in SA (Jefferies & Lambon Ralph, 2006). SA patients' inconsistency across different kinds of semantic judgement would be expected if different tasks placed varying demands on control processes. The effects of varying control demands were apparent on a semantic association task (the Camels and Cactus test; Bozeat, Lambon Ralph, Patterson, Garrard, & Hodges, 2000): SA patients (but not SD patients) performed most poorly on those trials where it was difficult to elucidate the relevant semantic relationship and reject the distractors.

The errors made by SD and SA patients in picture naming were consistent with the distinction between degraded knowledge and impaired control. Both groups produced predominately semantic rather than phonological errors, indicating a semantic locus of impairment. However, while SD patients made co-ordinate (cow → "horse") and superordinate (cow → "animal") errors, SA cases made additional errors of an associative nature (e.g., squirrel → "nuts"; glass → "ice"; lorry → "diesel") that almost never occurred in SD. Patients with SD typically incorrectly name objects as highly familiar and prototypical members of their class (e.g., naming all small mammals as "dog" or "cat"; Hodges, Graham, & Patterson, 1995; Woollams, Cooper-Pye, Hodges, & Patterson, 2008). This reflects the fact that fine-grained item-specific knowledge degrades early on in this condition – therefore the damaged semantic system is likely to be driven by highly typical features that are common to

many exemplars (Rogers et al., 2004). Associative errors occur very rarely, since these are indicative of object-specific knowledge that is lost in SD (for example, to produce “nuts” to a picture of a squirrel, the semantic system must contain some fairly specific information about the feeding habits of squirrels). In contrast, SA patients did produce these sorts of responses, suggesting that they continued to activate some item-specific information and therefore that the underlying store of semantic knowledge was relatively intact. However, SA patients appeared to have difficulty regulating their semantic activation in order to select the appropriate target name over other highly active but task-irrelevant responses. The naming of SA patients improved substantially when they were provided with phonological cues, again indicating that knowledge about the target names was still present within the semantic system. These cues may have acted as a source of external constraint over activation in the semantic system, reducing the internal control requirements necessary for selecting the correct response (Jefferies & Lambon Ralph, 2006; Jefferies, Patterson, & Lambon Ralph, 2008). Cueing produced much smaller effects in SD, presumably because little phonological information was generated from semantics to combine with the phonemic cues.

This semantic control impairment aligns with a large body of neuroimaging evidence implicating the left inferior prefrontal cortex in controlled semantic processing (for reviews, see Badre & Wagner, 2002; Thompson-Schill, Bedny, & Goldberg, 2005). This region is commonly activated in semantic tasks and shows increased activation when semantic tasks require selection amongst competing alternatives (Moss et al., 2005; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill, D'Esposito, & Kan, 1999) and when they require semantic retrieval from weak or poorly specified cues (Bunge, Wendelken, Badre, & Wagner, 2005; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001). Left prefrontal lesions were present in the majority of SA patients studied by Jefferies and Lambon Ralph (2006) but two patients presented with damage only in posterior areas and centred on the

temporoparietal junction (most of the other patients had large lesions encroaching on both areas). The consequences of these diverse lesions on semantic cognition were very similar: patients showed poor semantic control regardless of whether prefrontal or temporoparietal cortex was damaged (see also Berthier, 2001), suggesting that semantic control may involve a distributed network of brain regions. This proposal is consistent with recent approaches to cognitive and executive control more generally. While cognitive control has traditionally been associated exclusively with the prefrontal cortices, recent work has highlighted the importance of a distributed network of frontal and temporoparietal regions (Collette, Hogge, Salmon, & Van der Linden, 2006; Peers et al., 2005). Prefrontal and temporoparietal cortex show coupled activation during the performance of executive tasks, particularly in the context of working memory (Collette et al., 2005; Collette & Van der Linden, 2002; Crosson et al., 1999; Garavan, Ross, Li, & Stein, 2000).

Relevance to STM deficits

These findings show that damage to core semantic representations (in SD) dissociates from impairment to the control processes that are recruited to access and manipulate these representations (in SA). Could either of these impairments explain the semantic STM profile in which semantic performance is disproportionately affected when multiple items must be retained over a delay? The degradation of semantic representations that lies at the heart of SD is an unlikely candidate, since STM impairments in this condition are closely related to the status of individual word meanings. Although SD is associated with poor immediate serial recall (ISR) for words, this deficit is restricted to poorly-understood words that are also failed in comprehension tasks (Jefferies et al., 2004; Patterson et al., 1994). This is rather different to the situation in semantic STM cases, who show poor recall of words even when comprehension of individual word meanings is intact. Furthermore, the errors made by SD

cases are primarily phoneme migrations in which segments of phonology from different words are blended together (Jefferies, Hoffman et al., 2008; Knott et al., 1997; Majerus et al., 2007; Patterson et al., 1994). Semantic STM cases on the other hand usually make omissions, serial order errors or intrusions from previous lists in ISR (Martin & Lesch, 1996).

The alternative semantic deficit, impairment to control processes observed in SA cases, is more promising. SA patients *are* inconsistent across tests with different task demands, even when the same words are being probed, because their success depends on how much control is required to access and manipulate the semantic representations required for the task in hand (Jefferies & Lambon Ralph, 2006). Verbal STM tasks, in which multiple words must be activated and maintained simultaneously, might be expected to place greater demands on control processes than standard semantic tasks that feature single words. Indeed, when we tested a subset of the SA patients described above on an ISR task, they made an abnormally high number of serial order errors (Jefferies, Hoffman et al., 2008). Some of these patients consistently distorted the list order in a particular way, beginning their response with the final list item. This might reflect an inability to resolve competition between different activated list items, in line with proposals that cognitive control mechanisms support serial order memory when span is exceeded (Hazy, Frank, & O'Reilly, 2006; O'Reilly, Braver, & Cohen, 1999; O'Reilly & Soto, 2002). Rather than directing attention first to early list items, patients immediately responded with the final list item, which presumably was most accessible as a result of its recent presentation. A similar explanation has been proposed for the same error pattern in semantic STM patient AB: Martin and Lesch (1996) suggested that AB suffered from a failure of inhibition. More recent work has revealed poor inhibition in semantic STM patient ML (Hamilton & Martin, 2005, 2007). ML is highly susceptible to proactive interference in STM tasks, reflecting an inability to inhibit strongly activated but irrelevant representations and suggesting that an underlying cognitive control deficit

underlies his STM problems. Our hypothesis in this study was rather similar: that semantic STM patients suffer from poor control over their semantic representations, with the result that maintaining multiple words in STM is impaired. However, our working hypothesis was that these problems are not limited to STM and could be observed in any semantic task that placed sufficient demands on control mechanisms.

To investigate this possibility, we explored semantic processing in two semantic STM cases. We compared these patients to a case-series of individuals with SA who exhibited poor semantic control across a range of non-STM tasks (Jefferies & Lambon Ralph, 2006). We expected the semantic STM patients to show mild semantic difficulties on tasks, irrespective of the STM load, and we expected these difficulties to be most pronounced on tasks that required a high degree of semantic control (e.g., retrieval from a weakly specified cue or selection from highly activated competitors). The SA cases were tested with the same tasks to establish whether their pattern of impairment was similar. There were two components to our investigation. First, we investigated verbal STM in the two semantic STM cases to establish that their deficits related to poor recall of lexical-semantic information. The SA cases completed the same tasks, with the expectation that they would show a similar pattern of impairment as a result of their semantic control deficits. Second, we examined semantic processing using a range of tasks. We began by using a standard test battery that has previously revealed multi-modal semantic deficits in SA and SD (Bozeat et al., 2000; Jefferies & Lambon Ralph, 2006). Semantic performance was also tested under more demanding conditions with further tests that emphasised speeded responding. In these tests we minimised the involvement of STM by using visual presentation, allowing us to assess whether semantic STM patients have a more general difficulty completing semantic tasks under demanding conditions. Finally, we gave the patients word production tasks which

required cognitive control to complete the task successfully. We expected that performance in the semantic STM cases and the SA group would worsen as control requirements increased.

Case Descriptions

A summary of biographical and neuroimaging information and aphasia classifications for all patients is given in Table 1.

-Table 1 around here-

Semantic STM Patient: JB

JB was a 51 year-old man who left school aged 15 and worked as a factory foreman until he suffered a left-hemisphere haemorrhagic CVA in April 2005. He was initially densely amnesic and did not recognise family members for two weeks post CVA. JB's language profile assessed four months post stroke was closest to transcortical sensory aphasia. His speech was fluent and his ability to repeat verbal material was excellent but he displayed marked comprehension and word-finding difficulties. He correctly named seven of the first seventeen items on the Boston Naming Test without cues (BNT; Kaplan, Goodglass, & Weintraub, 1983). We began the investigation reported here in February 2006, by which time his language skills had improved substantially. His comprehension and spontaneous speech appeared normal, though he still complained of occasional word-finding difficulty and amnesia for recent events. At this point, he named 42/60 items on the BNT without cues.

A series of axial and coronal MRI slices for JB are shown in Figure 1 (radiological convention with the left hemisphere shown on the right). The damage resulting from the haemorrhage was confined to the left hemisphere. The superior temporal gyrus and sulcus were intact along their lengths, and the anterior part of the temporal lobe was also intact. Loss of tissue was primarily along the fusiform and inferior temporal gyri (including underlying

white matter), and to a lesser extent the middle temporal gyrus. The parahippocampal, perirhinal and entorhinal cortices seemed to be intact, as did the hippocampus. There was also a widening of the left sylvian fissure and the posterior horn of the lateral ventricle, which may indicate some additional damage in the surrounding cortex.

-Figure 1 around here-

Semantic STM Patient: ABU

ABU was a 52 year-old man who left school at the age of 15 and was employed as a sheet metal worker for a number of years. He experienced a CVA in June 2003, resulting in right-sided hemiparesis. A CT scan obtained at this time was inconclusive. The left lateral ventricle appeared enlarged and the grey-white matter contrast in the basal ganglia was reduced on the left side, which could indicate a diffuse left-hemisphere partial infarction. We were unable to obtain an MRI scan for ABU due to counter indications. ABU presented acutely with word-finding difficulty and mild comprehension problems, correctly naming nine of the first 23 items in the BNT (without cues). However, his language abilities recovered after this initial period. When first seen by us in December 2006, his comprehension was good and his speech was fluent though punctuated by occasional hesitations. His phrase length also appeared slightly reduced. He could successfully name 43/60 pictures in the BNT.

Semantic Aphasia Group: Aphasics with Multi-Modal Semantic Impairments

These two patients were compared with a case-series of eleven stroke aphasics recruited from stroke clubs and speech and language therapy services in Manchester, UK. Patients with verbal comprehension deficits were initially screened and enrolled in the study if they failed both picture and word tests of semantic association (Camels and Cactus test;

Bozeat et al., 2000). Every case had chronic language impairment from a CVA at least a year previously. Their semantic deficits are described in more detail later. Ten of these cases have been studied previously and their semantic problems shown to be associated with a failure to control semantic activation in a task-appropriate fashion (Jefferies & Lambon Ralph, 2006). An additional case, JD, was referred to us more recently and included in the case-series for the present study. Although he failed a number of semantic tasks in multiple modalities, he was one of the least impaired patients in the case-series.

Control Participants

A single set of ten individuals served as controls for most of the experimental tasks reported in this paper. This control group had a mean age of 61, which did not differ significantly from the mean age of the patients ($t(21) = 0.70, p = .49$).

Statistical Analyses

When comparing the performance of individual patients to that of our control group, we used the modified t-test method recommended by Crawford and Garthwaite (2002). We also employed a number of standardised tests with existing norms. For these we used published cut-offs to determine whether a patient was impaired or, where these were not available, we considered any score more than two standard deviations below the published mean to be impaired.

Background Neuropsychology

Method: Patients were tested on a number of non-verbal attentional/executive tasks, namely Raven's Coloured Progressive Matrices (Raven, 1962), the Brixton test of spatial anticipation (Burgess & Shallice, 1996), the Elevator Counting subsets of the Test of

Everyday Attention (Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994) and the Wisconsin Card-Sorting Test (WCST; Milner, 1964; Stuss et al., 2000). These tests recruit a number of abilities associated with executive function. In the Brixton test, the patient attempts to predict the path of a moving dot through a spatial array. At various points in the test and unknown to the patient, the rules that govern the dot's movement change, requiring the patient to inhibit the previous rule and respond to the new rule. Similar processes are required in the WCST, in which sorting rules must be updated on the basis of feedback from the experimenter. The Elevator Counting test features two conditions. The first is counting without distraction, in which the patient simply counts a series of tones. In the "with distraction" condition, high and low-pitched tones are interspersed but the patient counts only the low-pitched tones. This involves shifting attention between the tones and the tally and inhibiting the tendency to respond to all of the tones. Finally, the Raven's coloured matrices test is a measure of fluid intelligence in which the patient selects the appropriate block to match with a visual pattern. On the more difficult trials, the patterns vary on a number of different dimensions that must be attended to simultaneously and integrated in an abstract way in order to select the correct response, and thus the test is executively demanding.

Patients also received tests of forward and backward digit span (Wechsler, 1987) and visual processing was assessed using several subtests from the Visual Object and Space Perception battery (VOSP; Warrington & James, 1991) and immediate copies of the Rey complex figure (Rey, 1941).

Results and Discussion: Scores are shown in Table 2. In all tables and figures, the semantic STM cases JB and ABU are presented on the left and the semantic aphasic cases on the right, arranged in order of their comprehension impairment (word-picture matching scores). There was some evidence of mild executive dysfunction in JB and ABU. JB exhibited weakness on the Raven's test and the Brixton test while ABU performed poorly on

the Wisconsin test, scored just above the minimum cut-off score on the Brixton test and showed some weakness on the Elevator Counting test. As no norms existed for the age group of JB and ABU for Raven's Coloured Matrices, we also tested them with the standard matrices set (Raven, 1992). JB scored 23/60, which fell below the 5th percentile for his age group. ABU scored 34/60, reaching the 10th percentile.

The SA patients all showed evidence of executive dysfunction, albeit in a somewhat variable manner, with different patients failing different tests. This might be because different tasks required different executive functions. Evidence from healthy subjects suggests that "executive" tasks in fact tap a number of correlated but separable functions (Miyake et al., 2000, for example, identified separate shifting, updating and inhibition components). Variation in patient scores might reflect variation in the degree of impairment to each of these components. Another possibility is that the patients were affected in different ways by the modalities tapped by each test (e.g., the elevator counting uses auditory presentation and a verbal response while the Brixton test is visuospatial and uses a pointing response). In line with this possibility, digit spans and visuospatial processing were impaired rather variably in the SA group, potentially reflecting additional visual or phonological deficits in some patients following their large lesions. Poor comprehension of task instructions could also have contributed to the impaired executive scores of the SA patients, although this is unlikely to account for JB and ABU's deficits. These patients have very good verbal comprehension and successfully followed complex instructions on other tasks we have presented to them. Moreover, in these two cases, digit spans were normal, suggesting preservation of phonological STM, and they scored well on the VOSP tests indicating good visuospatial skills (although ABU's copy of the Rey figure was mildly impaired).

-Table 2 around here-

Section 1: Verbal Short-Term Memory

In the first set of experiments, we investigated verbal STM in JB and ABU to establish that they had particular difficulty retaining lexical-semantic information. If this was the case, we would expect them to perform well on tests requiring only phonological storage but more poorly when semantic information was relevant to recall. Thus, the profile required to class them as semantic STM cases was as follows: (1) Better performance on a rhyme than a category probe task, as the category task explicitly taps semantic knowledge about the words maintained in STM (Martin et al., 1994). (2) Good recall of letters and nonwords in ISR, as these items are maintained in phonological form. (3) Impaired ISR of word lists, relative to nonword recall (i.e., a reduced lexicality effect), because lexical-semantic knowledge makes a larger contribution to the recall of words (e.g., Hulme et al., 1991; Jefferies et al., 2004). (4) A normal phonological similarity effect in letter ISR, as this is associated with normally functioning phonological STM (Conrad & Hull, 1964). We gave the same tasks to members of the semantic aphasic case-series to investigate whether a similar profile of STM impairment would be present in the context of more severe semantic impairment. Five SA patients completed the ISR tasks. These five all fit the diagnostic criteria of transcortical sensory aphasia (TSA), characterised by good repetition, fluent speech and poor comprehension (Albert, Goodglass, Helms, Rubens, & Alexander, 1981; Berthier, 2000). Therefore, they could complete list repetition tasks without deficits of phonology or speech output dominating their results. The category and rhyme probe tasks required no spoken output and were completed by a larger number of patients (although JM, KH and MS withdrew from the study prior to this test being completed).

Category and Rhyme Probed Recall

A hallmark of impaired semantic STM is a dissociation between tests featuring category and rhyme probes (Martin et al., 1994). Semantic STM patients are unable to verify whether words in a spoken list belong to the same category as a probe word presented after the list, even though they can demonstrate knowledge of category membership when items are encountered individually. Demonstration of this effect in JB and ABU was important to establish their status as semantic STM patients.

Materials: Category and rhyme tasks were based on those of Martin et al. (1994). The rhyme test featured list lengths from one to nine items. Each list consisted of non-rhyming words. For half of the lists, this was followed by a probe that rhymed with one of the list items (e.g., list: DOG, WISH, HAT; probe: DISH). For the remaining lists, the probe was non-rhyming. There were 20 lists for each of lengths one, two and five and 24 lists for each of the remaining list lengths. Methods for creating the category lists were the same, except that each word belonged to one of nine categories: animals, body parts, clothing, flowers, fruits, insects, kitchen items, trees and types of weather. For half of the lists, the probe shared its category with one of the list items; categories were not otherwise repeated within a list (e.g., list: OAK, RAIN, SOCK; probe: SNOW). Category lists ranged from one to seven items in length.

Procedure: For both tests, lists were presented verbally at a rate of one item per second. The probe followed the list after a two-second pause. Subjects responded “yes” or “no” according to whether a probe rhymed/was in the same category as a list item. The first two list lengths were preceded by three practice trials during which the experimenter gave feedback and highlighted any errors. For the patients, testing began with all of the one-item lists. If the patient was at least 75% accurate at this list length, testing continued with the two-item lists, with list length increasing in this manner until the patient’s accuracy for a particular length fell below 75%. Span was defined as the maximum length at which accuracy

was 75%; if this cut-off fell between two lengths, linear interpolation was used to calculate span. The procedure in controls was the same except for two modifications designed to reduce the duration of the testing session. First, testing began with three-item lists for the category test and four-item lists for the rhyme test. Second, if a participant correctly responded to ten consecutive trials at any list length, they immediately proceeded to the next list length.

In a separate session, we used a single-item sorting task to examine whether the patients knew which category each test item belonged to. We presented the patients with a display showing the category names alongside a photographed exemplar of each category. Each item from the main test was read out individually and the patient pointed to the category they thought the item belonged in. Controls did not complete this section of the test.

Results: Performance on these tasks is given in Table 3. Both semantic STM patients performed within the normal range on the rhyme span task, with JB exceeding the mean span in controls. However, in the category test both patients failed on the three-item lists, indicating impaired semantic STM. Therefore, the category spans of these cases were comparable to other reported semantic STM patients and they showed a dissociation between semantic and phonological retention as expected. Both patients were largely accurate when sorting individual items into categories, scoring above 90%. However, we rescored the category probe task, excluding any trials that featured a target or probe word the patient had not sorted correctly (figures in parentheses in Table 3). This change had little effect on their accuracy, suggesting that their poor category spans were not simply a consequence of impaired category knowledge². Generally, the SA cases performed poorly on the category

² The small improvement in JB's accuracy on the 3-item lists was sufficient to exceed the 75% cut-off for this list length. However, when we tested JB with 4-item lists he achieved a score of 61%, which was considerably less accurate than controls.

and rhyme tasks; the two most severely impaired cases were unable to respond accurately to the shortest lists. However, three patients (ME, PG, BB) showed a dissociation between the two tasks, scoring more poorly on the category task. Low rhyme spans in this group of patients may reflect impairments to phonological storage. In line with their more severe semantic impairments, the two most impaired SA cases were unable to sort the items into categories even when presented individually. However, single-item sorting was relatively intact for the other patients. As for the semantic STM patients, excluding items that patients had not sorted correctly produced little improvement in the STM version of the task.

-Table 3 around here-

Immediate Serial Recall of Words and Nonwords

Semantic STM patients show a reduction in the advantage for recall of words over nonwords, reflecting an inability to use lexical-semantic information to aid STM (Martin & Lesch, 1996).

Control participants: Control data for this experiment are reported in Jefferies et al. (2005). Ten participants aged between 50 and 70 were tested. All left full-time education aged between 14 and 16.

Materials and Procedure: The test comprised lists of words and nonwords presented for ISR (taken from Gathercole, Pickering, Hall, & Peaker, 2001). Controls and semantic STM patients received 20 word lists and 20 nonwords lists in total. Half contained four items and half contained five items. Additionally, five SA patients were tested – as described above, these were the five individuals with most intact repetition skills. To avoid floor effects, they completed two, three and four-item lists. There were 30 word and 30 nonword lists in total. The words and nonwords, which were not repeated in the course of the

experiment, were blocked using an ABBA design and were presented auditorily at a rate of one item per second.

Results: Accuracy on this task is given in Figure 2. JB was highly accurate: he performed within the range of controls on the word lists and actually exceeded the maximum control score when recalling nonwords (JB: 57%; Control range: 18-46%). The size of his lexicality effect (i.e., the difference between word and nonword accuracy) was significantly smaller than that of controls (modified $t(9) = 2.76, p < .05$). ABU recalled words more poorly than controls but his nonword recall was within the control range; he recalled 32% of nonwords accurately. ABU's lexicality effect was also smaller than controls (modified $t(9) = 3.64, p < .01$). The five SA cases also showed a reduced advantage for word recall over nonword recall: there was a significant lexicality by group interaction when the SA patients were compared with controls ($F(1,13) = 16.8, p = .001$).

-Figure 2 around here-

Immediate Serial Recall of Phonologically Similar and Dissimilar Lists

An advantage for phonologically dissimilar material over similar sounding items has often been taken as a marker of phonological coding in verbal STM (Conrad, 1964; Conrad & Hull, 1964). Patients with phonological storage deficits present with reduced, or sometimes reversed, phonological similarity effects (Martin & Breedin, 1992). However, normal effects of phonological similarity have been reported in semantic STM patients (Martin & Lesch, 1996; Martin et al., 1994).

Control Participants: Control data from twelve participants are reported in Jefferies et al. (2005). Ten of these participants also completed the previous experiment.

Materials and Procedure: Participants recalled lists of phonologically similar and dissimilar letters in serial order. The phonologically similar set contained the letters E, C, T,

P, V, B, G, D and the dissimilar set consisted of the letters W, S, Q, Y, R, J, F, L, following Knott et al. (2000). There were forty lists; half contained four items and half contained six items. The phonologically similar and dissimilar letters were blocked using an ABBA design and items were read aloud at a rate of one item per second for spoken recall.

Results: Mean item accuracy across both list lengths is shown in Figure 3. JB performed at a similar level to controls though ABU was rather less accurate. One possible explanation for ABU's difficulty on this task is that a small set of letters were repeated several times within the experiment, leading to high levels of proactive interference. This would be consistent with a cognitive control explanation of ABU's STM problem (Hamilton & Martin, 2005). In any case, it is important to note that both semantic STM patients showed a significant effect of phonological similarity (JB: $\chi^2 = 8.72, p < .005$; ABU: $\chi^2 = 22.3, p < .0001$; all tests two-tailed), in line with findings from previous semantic STM cases. Four of the five SA patients also showed a significant effect of phonological similarity ($\chi^2 > 5.01, p < .05$), the exception being LS ($\chi^2 = .02$). LS made a number of perseverative and letter completion errors (e.g., "BBC") that may have prevented the appearance of any effect.

-Figure 3 around here-

Discussion of Verbal Short-Term Memory Results

In this section, we confirmed that JB and ABU's problems with verbal STM were a result of impaired ability to use semantic information in recall. Their performance on tasks tapping phonological retention was good: both demonstrated normal ISR of nonwords and were sensitive to phonological similarity in letter lists. The phonological retention capacity of JB appeared completely spared, while ABU's scores were a little lower but not abnormal. In ISR, they showed a reduced lexicality effect; neither could recall word lists as well as their performance on nonword lists would predict. They were also impaired on the category probe

test but performed well with the rhyming probes. This pattern of performance is consistent with other cases of impaired semantic STM (Martin & He, 2004; Martin et al., 1994). Indeed, the striking dissociation between phonological and semantic span in patient JB indicates a particularly pure case of the deficit. Our patients were largely accurate at categorising individual words and their failure on the category STM task remained even when mis-categorised items were excluded from the analysis. This suggests that damage to core semantic representations (of the kind observed in SD) cannot explain the patients' semantic STM impairment. Instead, poor STM could be a consequence of disruption to a buffer specialised for the retention of lexical-semantic information (Martin et al., 1994). An alternative view is that impairment to more general semantic control processes could be responsible, assuming that the STM version of the task placed greater demands on these processes than the single-item task. SA patients, who have semantic control impairments on a range of tasks, showed a broadly similar STM profile to the semantic STM cases. They were also impaired on the category probe task, even when errors in category knowledge were taken into account. Rhyme probe performance was variable but tended to be more intact than the category test. SA patients also showed reduced lexicality effects and normal phonological similarity effects, suggesting that they also relied mainly on phonology and not semantics to complete ISR tasks.

Section 2: Semantic Processing

In this section, we examined our semantic STM cases using a number of semantic memory assessments that did not load heavily on STM, in order to determine whether their semantic problem is specific to STM or is a more general deficit. On each task the semantic STM patients were compared to members of the SA case-series to establish whether similar impairments were present in this group. There were three components to this section: (1)

Standard semantic battery. Patients received a battery of verbal and non-verbal semantic tasks that we have used previously with SA and SD patients (Bozeat et al., 2000; Jefferies & Lambon Ralph, 2006). In common with previous semantic STM cases, JB and ABU scored well on these tests, leading us to administer some more demanding assessments. (2) Speeded semantic tasks. Patients performed naming and synonym judgements at speed. Accuracy and RTs revealed mild semantic impairments on these tasks. (3) Manipulation of control demands. Patients completed three tests considered to have high semantic control demands, to explore whether their semantic deficit was consistent with an underlying impairment of semantic control.

Standard Semantic Battery

Method: Semantic processing was assessed using a 64-item semantic battery, which assessed knowledge of the same 64 items across different input and output modalities and types of semantic judgement. The tests included were: (a) Camel and Cactus Test (Bozeat et al., 2000); a test of semantic association similar to the Pyramids and Palm Trees Test (Howard & Patterson, 1992) in which subjects decided which of four semantically related items was most associated with a stimulus (e.g., does CAMEL go with CACTUS, TREE, SUNFLOWER or ROSE). There were two versions: in one, the probe and choices were coloured pictures; in the other, they were presented as written words that were read aloud by the examiner. (b) Spoken word-picture matching: subjects matched spoken names to pictures. There were nine semantically related foils. The target and foils were black and white line drawings from the Snodgrass and Vanderwart (1980) set. (c) Spoken picture naming: the patients were asked to name each item presented as a Snodgrass picture. We also used the Environmental Sounds test (Bozeat et al., 2000). This test contained recorded sounds from six categories: domestic/foreign animals, human sounds, household items, vehicles and musical

instruments (N=48). There were three conditions: matching sounds to pictures; sounds to written words, and spoken words to pictures. On each trial, the target was presented with nine within-category distractors. Finally, picture naming was assessed using the BNT. Patients were presented with all 60 pictures from the test and for any items they could not name were given a phonemic cue (typically the first two phonemes of the word) and another opportunity to name. Although picture naming is not a pure semantic task, most researchers agree that semantic processing is a necessary first step in lexical production and naming errors can be informative about the nature of a patient's deficit (Lambon Ralph, Moriarty, & Sage, 2002; Schwartz, Dell, Martin, Gahl, & Sobel, 2006). An error analysis was therefore conducted, combining data from both naming tests. Single-word errors were classified as semantic if they shared a co-ordinate, superordinate or associative relationship with the target and as phonological if they shared at least one phoneme with the target in the correct position in the word. Errors meeting both criteria were classed as mixed. An "other" category contained visual errors, perseverations and other errors unrelated to the target. Errors of omission were counted separately and we included circumlocutions in this category.

Results and Discussion: Results are shown in Table 4. The semantic STM cases were largely intact on this battery; they showed mild impairments on the BNT and one other semantic test. In contrast, the SA cases showed a range of impairments, with all patients failing both verbal and non-verbal tests. The performance of the SA cases on these tasks is described in more detail by Jefferies and Lambon Ralph (2006). In summary, patients showed consistency when the same task was presented in different modalities (e.g., sound-picture vs. sound-word matching) but were highly inconsistent when compared on tasks requiring different types of semantic judgement (e.g., simple matching tasks vs. semantic association tasks). Performance on the Camel and Cactus association test was worst on trials where it was difficult to elucidate the relevant semantic dimension and where it was difficult to reject the

distractors, suggesting that patients had difficulty selecting and attending to relevant semantic information. The high scores of our semantic STM patients prevented us from conducting similar analyses of their results.

The analysis of picture naming errors is presented in Table 5. Although JB and ABU made fewer errors overall, their distribution was similar to that of the SA cases. JB and ABU tended to make semantic or omission errors, although ABU also made a handful of phonological errors. Likewise, semantic errors and omissions accounted for the majority of errors in the SA cases (the only major exception to this pattern was patient LS, who made frequent perseverative errors). This distribution of error types has been associated previously with semantic impairment in SD (Lambon Ralph, McClelland, Patterson, Galton, & Hodges, 2001) and stroke aphasia (Dell, Schwartz, Martin, Saffran, & Gagnon, 1997; Lambon Ralph et al., 2002; Schwartz et al., 2006).

-Table 4 and Table 5 around here-

Speeded Picture Naming and Synonym Judgement

The standard semantic battery provided little evidence for general semantic impairments in JB and ABU, although their errors in picture naming were consistent with a semantic impairment. However, it was possible that mild semantic problems would be evident on more demanding tasks. As discussed in the Introduction, semantic STM patients AB and ML showed abnormalities in category judgements when performing under timed conditions (Martin & He, 2004; Martin et al., 1994). Here, we assessed semantic processing in JB and ABU using two timed semantic tasks: picture naming and synonym judgement. We chose these particular tests as they have different processing and response requirements (picture vs. verbal stimuli and verbal response vs. forced-choice selection). Impaired performance on both tasks would suggest a central semantic impairment rather than simply

difficulties with a particular type of stimulus or mode of responding. We also minimised the STM demands of the tasks. In the speeded category judgement task that revealed impairment in previous patients, the first item appeared visually for one second and the second item was then presented verbally, raising the possibility that poor retention of the first item caused the decrement in performance, rather than a central processing deficit. In our tests, items were presented visually via a computer monitor and remained on screen until a response was made.

Participants: Since accuracy and RT data were collected in this experiment, it was not possible to compare the semantic STM cases with the full set of SA patients, many of whom would not produce enough correct responses for an RT analysis. Therefore, the four patients with the mildest semantic impairments were selected to take part (JD, NY, SC, PG).

Method: Both tests were administered using a 15" laptop computer monitor running Eprime software. Participants were instructed to respond as quickly and accurately as possible but no time limit was placed on responses. (1) Picture naming: this involved 48 line drawings from the Snodgrass and Vanderwart (1980) set (24 living items and 24 non-living). Presentation rate was controlled by the participant: upon pressing the spacebar, a picture appeared, accompanied by a 200ms tone. For controls and for the semantic STM patients, time between the appearance of the picture and the onset of their first response was measured using an electronic voice key. The voice key was not used with the SA cases, who often made extraneous responses and comments before naming; instead, a digital recording of the session was analysed using WavePad software (NCH Swiftsound) to obtain response latencies. (2) Synonym judgement (Jefferies, Patterson, Jones, & Lambon Ralph, submitted): participants saw a stimulus word and three possible target words and indicated which target word was synonymous with the stimulus. The stimulus word was presented near the top of the screen, while the three possible responses appeared simultaneously beneath it. There were 96 trials in total. Participants responded by pressing 1, 2 or 3 on the computer keyboard. They controlled

the presentation rate by pressing the spacebar when they were ready for each trial and the computer recorded latencies from the onset of the stimulus until a response was made. To ensure that patients were able to read the test items accurately, in a separate session the stimuli were presented as above and patients were asked to read them aloud as quickly as possible.

Results: Accuracy and reaction times are shown in Table 6. In picture naming, JB correctly named fewer pictures than controls, as did the SA cases. ABU's accuracy did not differ from controls. To analyse reaction times, RTs for incorrect responses were discarded, as were voice key errors (one response each for JB and ABU and 1.9% of responses for controls). Outliers beyond two standard deviations of a participant's mean were also excluded. The analysis revealed that both semantic STM patients were significantly slower to name picture than controls, with the slowing particularly evident in JB. In addition to their poorer accuracy, three of the SA cases were abnormally slow.

-Table 6 around here-

Reading of the synonym judgement stimuli was largely accurate: JB read 97% of the words correctly and ABU read 91%. In the SA group, JD, NY and PG were 99%, 82% and 91% accurate respectively, but patient SC was unable to read most of the words and therefore could not complete the synonym judgement task. When judging synonyms, all of the patients were significantly impaired. JB and ABU's accuracy was within the range of the mild SA patients. Impairment on the synonym judgement task did not appear to be related to the patients' mild deficits in reading the items aloud since all of the patients remained significantly impaired when trials in which the target or probe word were read incorrectly were excluded from the analysis. To analyse RT, outliers that deviated by more than two standard deviations from each participant's mean were removed. JB responded more slowly

than controls but ABU was in the normal range. The SA patients were very slow to complete this task.

Discussion: These timed tasks revealed deficits of semantic processing in JB and ABU. JB named pictures less accurately than controls and both patients were impaired on the synonym judgement task. In addition, RTs were abnormally slow – for both patients when naming pictures and for JB when making synonym judgements. The magnitude of these impairments approached that of the milder aphasic cases. These findings suggest that semantic processing is not entirely normal in patients with semantic STM deficits, even when performing tasks with a minimal STM load. The presence of deficits on two rather different tasks suggests that the patients’ problems are not an artefact of a particular method of testing and represent a general problem in accessing semantic information. The final three experiments in this study were intended to provide further evidence for this semantic impairment and to investigate the nature of the deficit. Specifically, we were interested in whether the semantic deficit in JB and ABU reflected a problem with semantic control, as we have hypothesised for individuals with multi-modal semantic impairments following stroke, or was more consistent with degraded semantic knowledge, as is the case for patients with SD (Rogers et al., 2004). Since our semantic STM patients seemed to have very mild semantic deficits, we focused on semantically-driven word production tasks, as these tend to be more sensitive to semantic impairment than receptive tests.

Phonologically Cued Picture Naming

Providing phonological cues often improves picture naming in aphasia and this facilitation can be explained in a number of ways depending on the characteristics of the patients in question. One effect of providing phonological cues is to boost activation of the target word above that of its competitors (Lambon Ralph, Sage, & Roberts, 2000; Myers

Pease & Goodglass, 1978; Patterson, Purrell, & Morton, 1983), which may be particularly helpful for individuals with semantic control deficits that affect selection of semantic information. The SA patients in this study made numerous associative errors in picture naming (e.g., squirrel → “nuts”), suggesting that pictures did elicit some relevant semantic activation but that the patients failed to engage control processes in order to regulate this activation and select the appropriate response. Accordingly, they showed substantial phonological cueing effects in naming, suggesting that they often could resolve competition between potential responses with the aid of additional external constraints (Jefferies, Patterson et al., 2008). Furthermore, providing *miscues* that primed a semantic competitor had a negative effect on performance (Noonan, Jefferies, Corbett, Hopper, & Lambon Ralph, submitted). Patients with SD, on the other hand, showed little benefit from cueing as their degraded semantic systems provided insufficient initial semantic activation for cues to aid selection. JB and ABU did show effects of phonological cues in our background semantic testing. However, the patients were fairly accurate and cues were only given when they made an incorrect initial response, so there were relatively few trials in which cues were presented. This experiment examined phonemic cueing in a more systematic manner, providing cues before a response was made. In addition, we examined the effect of miscues that were inconsistent with the target response. These might be expected to exacerbate control problems by boosting the activation of competing representations. We were not able to test the semantic aphasic group in this experiment; however, several members of the case-series were tested with a similar experiment by Noonan et al. (submitted) and showed significant cueing effects and negative effects of miscues.

Method: Patients were presented with the 60 pictures of the Boston Naming Test (Kaplan et al., 1983) on three separate occasions. On each occasion, one-third of the items were preceded by a correct phonemic cue, one-third with a phoneme that cued a semantic

competitor (e.g., a picture of a tree with /b/ from bush) and one-third with no cue. Correct and incorrect cues were interspersed so that patients were unaware of which cues were helpful and over the three sessions each picture was paired once with a correct cue, once with a miscue and once with no cue.

Results: JB named 40/60 pictures without cues, 46/60 with correct cues and 35/60 when miscued. ABU named 41/60 pictures when no cue was provided, 51/60 with a correct cue and 37/60 when miscued. One-tailed McNemar tests revealed that both patients named more pictures when provided with correct cues compared to miscues ($p < .001$) and ABU showed a significant benefit of correct cues compared to no cue ($p < .001$) with this difference just failing to reach statistical significance in JB ($p = .073$). JB made a total of 19 semantic errors in the experiment, his remaining 40 errors consisting of omissions or circumlocutions. ABU made 29 semantic errors and 17 omission/circumlocution errors but also made four phonological errors and one apparently visual error (artist's palette → "heart"). Semantic errors made by both patients tended to be consistent with the presented cue (e.g., picture of octopus and /s/ → "squid").

Discussion: These effects are consistent with an impaired control explanation of the patients' deficits. Initial phonemic information is likely to boost the activation of representations consistent with the cue. When a correct cue was presented, this increased the likelihood of the patients retrieving the correct name, in line with the idea that their mild naming impairment resulted from competition between highly active competitors. Conversely, miscues led to fewer correct responses and a tendency to produce semantic errors consistent with the cue, suggesting that they promoted activation of semantic competitors that the patients failed to resolve. In another study, SA patients responded in a similar manner to phonemic cues and miscues (Noonan et al., submitted), providing further evidence for similarities between the SA and semantic STM cases. The behaviour of JB and ABU is less

consistent with degradation to the semantic knowledge store itself, as SD patients with this impairment are insensitive to phonological cueing (Funnell & Hodges, 1996; Hodges et al., 1992; Jefferies, Patterson et al., 2008).

Verbal Fluency

In verbal fluency tasks, participants produce as many exemplars of a given taxonomic category or beginning with a certain letter as possible within 60 seconds. The open-ended nature of the task means that responses are weakly constrained by the stimulus, emphasising the need for internal cognitive control over word retrieval (Baldo & Shimamura, 1998; Chertkow & Bub, 1990; Funnell & Hodges, 1996). In addition to the cognitive control required to retrieve a number of words on the basis of a single cue, it is necessary to inhibit previous responses so that they are not repeated, implicating a role for selection mechanisms (Hirshorn & Thompson-Schill, 2006). Impaired performance on verbal fluency tasks would therefore be consistent with a deficit to semantic control.

Participants: As above, KA and MS were excluded from this test due to inability to produce verbal output. Patient performance was compared with control data from 30 healthy participants aged between 54 and 82.

Method: Patients were given the name of a category or a letter of the alphabet and asked to produce as many exemplars as possible within one minute, without repetition. There were eight categories (animals, birds, fruit, breeds of dog, household items, tools, vehicles and types of boat) and three letters (F, A, S).

Results and Discussion: Figure 4 shows the number of correct responses by each patient. JB and ABU produced significantly fewer exemplars than controls in category fluency, providing further evidence for a mild semantic deficit (modified t-test for each patient: $t(29) = 2.77, p = .01$). ABU was also impaired at the letter fluency task ($t(29) = 2.45,$

$p < .05$) and all of the SA patients were severely impaired on both tasks ($t(29) > 2.28, p < .05$; the only exception being SC's score on letter fluency, which was not significantly impaired). Although verbal production deficits may have contributed to the SA cases' difficulties on these tasks, this is a less convincing explanation of JB and ABU's poor performance, since they both displayed fluent spontaneous speech in conversation. It is more difficult to *entirely* exclude the possibility that the patients' STM deficits contributed to their reduced fluency. Neither patient showed a tendency to repeat responses within a trial, suggesting they retained information about their previous responses. Moreover, both patients produced appropriate exemplars over the entire 60 second period, indicating that they retained the category/letter throughout. However, STM problems might still have contributed to their reduced production rate if, for example, the category was lost mid-trial and had to be reconstructed based on memory for previous responses. An alternative explanation is that the STM patients' poor performance stemmed from difficulties using control processes to selectively retrieve relevant lexical and semantic information. Damage to semantic representations themselves, as seen in SD, also impairs category fluency (Hodges et al., 1992; Marczinski & Kertesz, 2006). However, semantic deterioration in SD is graded by frequency; patients tend not to produce low frequency exemplars in category fluency or other tasks. In contrast, both semantic STM patients produced infrequent words among their responses (e.g., ABU produced "elk" for animals and JB produced "ptarmigan" for birds).

-Figure 4 around here-

Verb Generation

In the verb generation task, participants are presented with a noun and must generate a verb that is semantically associated with it. Although in some cases this task is no more difficult than simple word association (e.g., chair → sit), there are many common nouns for

which there are no obvious associated verbs (e.g., ant → ?). By manipulating the number of associates and the strength of association between nouns and verbs, this task has been used to investigate the effect of competing responses (Thompson-Schill et al., 1997; Thompson-Schill et al., 1998) and the need to engage in controlled semantic retrieval where cue association strength is low (Martin & Cheng, 2006). Trials in which there are no strongly associated verbs and those in which there are multiple strongly associated verbs are assumed to depend on semantic control processes to a greater extent than those that feature a single strongly associated verb.

Here, we administered Martin and Cheng's (2006) version of the task, which independently varied number and strength of verb associates. There were two aims to this experiment. First, as the verb generation task is a demanding test of semantic access, we expected to obtain further evidence for semantic impairment in JB and ABU. Second, the pattern of performance across conditions should provide clues to the nature of the semantic impairment, specifically whether it related to selection among competitors or to retrieval based on weakly specified cues.

Participants: In addition to JB and ABU, we tested the four mildest cases from the SA group (JD, NY, SC, PG).

Materials: A noun was presented and participants attempted to produce a verb that was semantically associated. The nouns were those used by Martin and Cheng (2006) and they differed along two variables: selection demand (the degree of competition between likely responses) and association strength (the strength of the relationship between the noun and most probable verb response). In the low selection condition, each noun was highly associated with a single verb (e.g., apple → eat). In the high selection-high association condition, each noun was strongly associated with two different verbs (e.g., door → open, door → close). Finally, the high selection-low association condition contained nouns for

which there were no strongly associated verbs: each noun was weakly associated with a number of verbs (e.g., rug → lay, rug → roll). There were 15 nouns in each condition, which were presented in a random order.

Procedure: Words were presented on a 15” laptop computer monitor. The noun appeared visually in the centre of the screen along with simultaneous auditory presentation. The word remained on screen until a response was made or the participant indicated that they were unable to think of a suitable word. Eight practice trials preceded the main test. If patients made a number of non-verb responses, they were reminded of the instruction to respond only with verbs. Responses were digitally recorded and analysed later to obtain RTs.

Results: Only patients JB and ABU could complete this task successfully. None of the SA patients were able to comply with the task instructions; they either did not respond at all or consistently gave multi-word or non-verb responses, despite prompting and repeated explanation. One patient (PG) began by giving very slow but valid responses but found the experience of generating these words so effortful that he requested the test be abandoned halfway through. Results for JB and ABU are given in Table 7, alongside data from the control group. Although RT is reported for the patients, this is based on small numbers of correct responses and we therefore focus our analysis on accuracy data.

JB performed flawlessly in the low selection condition but he was slightly less accurate for high selection-high association nouns and substantially error-prone for the high selection-low association nouns. His accuracy in this condition was significantly worse than in the low selection condition ($\chi^2 = 9.31, p < .005$). ABU was less accurate than JB in all three conditions but he also performed most poorly in the high selection-low association condition, which differed significantly from the low selection condition ($\chi^2 = 8.57, p < .005$). The majority of JB’s errors were failures to respond, though he did give a non-verb response

to one item (roof → “tiles”). ABU tended to make non-verb responses (81% of all errors), which were usually associated nouns (e.g., ear → “lobe”).

-Table 7 around here-

Discussion: This task provided further evidence for mild semantic impairment in patient ABU, who was impaired relative to controls when generating verbs on the basis of a weakly associated noun. Although JB was not impaired at a statistically significant level, he showed a similar pattern, performing least accurately in the weakly associated condition. The patients’ STM impairment could conceivably have contributed to their poor performance on this task, because although the stimuli remained on screen throughout each trial, the task instructions had to be retained throughout the test session. However, this possibility does not straightforwardly account for the differences in performance across conditions. Our patients showed particularly poor performance when generating verbs in the low-association condition, a pattern also shown by semantic STM patient ML (Martin & Cheng, 2006). This suggests that semantic STM cases have difficulty retrieving semantic information based on weakly associated cues, consistent with the hypothesis that poor semantic control underpins their problems. Indeed, four SA cases with more severely impaired semantic control were unable to complete the task at all.

General Discussion

This study investigated verbal short-term memory and semantic processing in two patients with semantic STM deficits. The semantic STM patients resembled previously reported cases in terms of their STM profile (Martin & He, 2004; Martin et al., 1994): both performed normally on a rhyme probe STM task but were impaired when responding to category probes. They showed a reduced advantage for words over nonwords in ISR but exhibited normal effects of phonological similarity. The major finding of the study was that

both patients showed mild deficits on semantic tasks that did not appear to be a direct consequence of their STM impairment. In common with previous cases, the patients were unimpaired on standard untimed semantic tasks. However, under time constraints deficiencies in accuracy and RT were apparent. Demanding verbal fluency and verb generation tasks also revealed impairments.

The semantic STM patients were compared with a case-series of SA patients, all of whom had more severe semantic impairments associated with poor control over semantic representations (Jefferies & Lambon Ralph, 2006). There was some evidence for commonalities between this group and the semantic STM cases. The SA patients showed a similar pattern of STM impairment, showing reduced lexicality effects and performing poorly on the category probe task. Deficits on the category probe task did not seem to be a consequence of impoverished semantic knowledge: patients performed poorly on trials containing targets and probes that they could correctly sort into categories. There was evidence of more widespread semantic deficits in these patients and, like the semantic STM cases, they were very impaired on verbal fluency tasks that required a high degree of cognitive control. The verb generation task, another demanding task that involves selection and controlled retrieval, proved too challenging for even the milder cases in this group.

Our interpretation of the present findings is that STM deficits in the two semantic STM cases we have described are a consequence of more general deficiencies in semantic processing. Specifically, they might arise from a mild impairment to control processes involved in the access and manipulation of semantic information. On this view, both semantic STM patients and SA cases with more severe semantic problems fall on a continuum of impairment in which the same aspects of controlled semantic processing are damaged but to different extents. Mild impairments to semantic control have a detrimental effect on a patient's ability to deal with the semantic aspects of verbal STM tasks (and other semantic

tasks that place large demands on controlled processing) but leave performance on less cognitively challenging semantic tasks intact. More severe control deficits affect less demanding single-word semantic tasks (e.g., picture naming, word-picture matching) in addition to control over semantic STM. In this section, we first deal with alternative interpretations of the data from JB and ABU before considering precisely how control might play a role in semantic STM tasks.

An obvious challenge to the explanation we have put forward is that our patients' deficits are adequately explained as impaired retention of lexical-semantic information over time. We attempted to minimise retention demands by presenting stimuli visually throughout each trial. Nevertheless, some subtle STM demands may have remained. For example, in the fluency tasks patients must self-generate responses over 60 seconds, requiring them to remember the task instructions throughout. In the synonym judgement task, the probe and three choices were available in visual form during each trial but one might argue that an intact lexical-semantic buffer is necessary to attend to each pair of words for long enough to compare them. The retention and control/selection demands of semantic tasks are difficult to separate, since most complex tasks involve the maintenance of task instructions over time or the ability to attend to multiple stimuli simultaneously. It is in part these requirements that make them demanding of cognitive control. More work is needed to separate which aspects of these patients' deficits can be attributed to control processes and which to maintaining task-relevant representations over time. Nevertheless, there is some unambiguous evidence from a test without STM demands: picture naming is a simple task involving single stimuli and this was mildly impaired in both patients.

Another possibility is that JB and ABU suffer mild damage to the semantic store itself. Our primary reason for rejecting this hypothesis is that the patients' STM deficits did not correspond to their knowledge of individual word meanings. In the category probe task,

both patients demonstrated good knowledge of individual word meanings and removing the few words they mis-classified from the analysis did not alter the outcome of the STM test. This contrasts with SD patients and non-progressive cases of semantic knowledge impairment, where impaired knowledge of word meanings accounts for the deficit in STM (Caza, Belleville, & Gilbert, 2002; Forde & Humphreys, 2002; Jefferies et al., 2004).

If the core deficit in STM cases is one of impaired cognitive control, why does this have a disproportionate effect on STM tasks? STM tasks might place particular demands on control processes because of the number of representations that must be maintained simultaneously. Subjects must resist interference from items presented on previous trials and there is evidence that semantic STM patients can have particular difficulty with this aspect of STM (Hamilton & Martin, 2005, 2007; Martin & Lesch, 1996). The category probe task has additional elements that emphasise controlled processing. It requires patients to retain a number of word meanings but also to compare each of those meanings with the probe and ascertain whether a match is present. There are at least two ways in which this comparison might be accomplished. Subjects might access semantic representations of list items and compare the features of each list item with the features of the probe. Sufficient feature overlap would indicate a category match. However, decisions must be made on the basis of the categories defined within the task and not merely by gross similarity (e.g., LILAC and MAPLE are rather similar, but are not a match because one is classed as a flower and the other as a tree). So alternatively subjects might use the semantic information retrieved to determine a category for each word and compare these categories to the category derived from the probe. Either method involves competition and selection demands of the kind envisaged by Thompson-Schill et al. (1997; , 1998), since a number of features or categories are retained simultaneously. Competition between features from different items could disrupt the assignment of categories or reduce the activation of individual features, causing matches to

be missed. Additionally, since only nine categories are used in the task and individual items are repeated, the possibility of proactive interference from previous trials is large. More work is needed to determine precisely which aspects of the task are disrupted in semantic STM patients – indeed, it is possible that different processes are deficient in different patients – but it seems plausible that semantic control may play a significant role in these deficits.

One obvious question is why the category probe task was disrupted in semantic STM patients but the rhyme probe task, which has apparently similar control requirements, was not. One possibility is that the control mechanisms recruited to deal with semantic representations are distinct from those involved in phonological judgements (Devlin, Matthews, & Rushworth, 2003; Fiez, 1997). Another is that the phonological version of the task was not as demanding as its semantic counterpart. Healthy controls perform slightly better on the rhyming task, suggesting that it is less taxing. The detection of two words that rhyme might be easier because the same criterion can be applied in every case: rhyming words always share identical phonology in the same place in both words. Detecting two concepts that belong to the same category is a more complex judgement involving the retrieval and comparison of a number of features or their categories. The criterion to detect a match varies considerably according to the particular items being considered (e.g., GOAT, SHEEP and ELEPHANT all belong to the animal category but goats and elephants are much less similar to one another than goats and sheep). Category judgements might therefore place greater demands on controlled processing than rhyme detection, explaining why the two tasks dissociated in our patients. In support of the idea that semantic and phonological representations share common control processes, semantic STM patient ML was affected by both semantic and phonological similarity in probed recall and showed abnormal interference effects for letters, which lack semantic content (Hamilton & Martin, 2007). There was also

some evidence that cognitive control was impaired more generally in JB and ABU. Both patients showed weakness on tests of non-verbal executive function.

How might semantic control deficits be realised in implemented models of semantic and lexical processing? A detailed consideration of this issue is beyond the scope of this investigation but we can offer some suggestions as to how control problems might map onto existing models. One model that has been used to account for picture naming and repetition in aphasia is the interactive activation framework of Dell and colleagues (Foygel & Dell, 2000; Schwartz et al., 2006). In the model, activation spreads between semantic, lexical and phonological nodes through bidirectional connections. Naming begins with activation of a set of semantic feature nodes corresponding to a particular object. Activation spreads through the network for a given number of time units, after which a jolt of activation is given to the lexical node with the highest activation level, boosting its activation significantly so that it far outstrips that of its competitors. Activation then flows once again through network and after further time steps jolts are applied to the most active phonological nodes, which are taken as the phonemes of the response. A lesion affecting the initial activation jolt could potentially mimic some of the effects seen in SA.³ Reducing the activation boost applied to the most active lexical node would increase competition between the target word and other lexical representations, which accumulate some activation as a result of their semantic similarity to the target. Alternatively, noise could be added to the jolt process so that competing lexical representations sometimes receive an activation boost rather than the target. In either case, the result would be a reduction in accuracy and increase in semantic errors. This kind of damage would be alleviated by cueing, as is seen in the patients. Activating the initial phonemic node of the target at the same time as its semantic features would increase the activation of the target but not its semantically related competitors, thus combating the effects

³ We are grateful to an anonymous reviewer for this suggestion.

of the disrupted jolt process. Although activation jolts are a specific feature of the interactive activation model, they illustrate a general principle that could be incorporated into models of semantic processing to account for control processes. Essentially, the jolts are the result of an external source of regulation over activation in the language system, which we attribute to semantic control. To account for performance across a range of tasks, this regulation must be applied flexibly, with different features or representations being activated or inhibited depending on the task being performed.⁴

There remains one major difference between the semantic STM patients reported here and existing patients in the literature and this is in the location of their lesions. Semantic STM problems have previously been associated with lesions to left prefrontal cortex. Patient ML, for example, had a large frontoparietal lesion that includes the left inferior frontal gyrus (Hamilton & Martin, 2007), an area strongly associated with semantic control in neuroimaging studies (e.g., Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Devlin et al., 2003; Moss et al., 2005; Thompson-Schill et al., 1997; Wagner et al., 2001). Our patient JB had damage to the posterior temporal lobe and ABU's damage, although harder to interpret, also appeared to spare the frontal lobe. One might conclude on the basis of this neuroanatomical evidence that semantic representations rather than control processes were affected. Why then do we favour the semantic control explanation? First, because the mismatch between the patients' comprehension of words and their ability to hold them in STM makes damage to semantic representations an unlikely explanation of their deficits. Second, because there is growing evidence that cognitive control is supported by a distributed network of brain regions, rather than relying exclusively on prefrontal cortex. Peers et al. (2005), for example, studied visual STM in frontal and parietal patients. Parietal patients displayed slower visual processing speeds than those with frontal lesions. However,

⁴ For an implementation of this sort of task-dependent regulation in a non-language domain, see Rougier et al (2005).

attentional control – defined as the ability to ignore irrelevant stimuli – was not selectively impaired in the frontal group; instead, it correlated with overall lesion size in both groups. The authors postulated that frontal and parietal cortices play similar roles in top-down attentional control. Our own studies of semantic control have revealed similar findings in the semantic domain; patients with temporoparietal lesions showed similar deficits in semantic control as those with damage in the prefrontal cortex (Jefferies et al., 2007; Jefferies & Lambon Ralph, 2006; Jefferies, Patterson et al., 2008). Similarly, neuroimaging studies of cognitive and executive control have reported temporoparietal activations (Collette et al., 2006; Collette et al., 2005; Garavan et al., 2000). Activity in this region has also been observed in controlled semantic tasks: for example, when resolving semantic ambiguity in sentences (Rodd, Davis, & Johnsrude, 2005) and when selectively attending to particular aspects of a stimulus (Cristescu, Devlin, & Nobre, 2006). Although the role of posterior regions in control over semantic memory specifically requires further study, it seems that an absence of frontal damage need not rule out problems with control of semantic representations.

As a final point, we would not wish to claim that *all* STM deficits can be explained through poor control mechanisms. Deficits of phonological STM have been linked to faulty rehearsal processes and impairment of a phonological buffer (e.g., Martin et al., 1994; Vallar & Baddeley, 1984; Warrington & Shallice, 1969). There is also considerable evidence that verbal STM problems in SD are closely related to the degradation of their semantic knowledge (e.g., Patterson et al., 1994). However, poor cognitive control might account for those cases in whom semantic aspects of STM are impaired in the absence of either a phonological STM impairment or degraded semantic knowledge. We have demonstrated in two such patients that mild semantic processing deficits can be revealed with sufficiently

sensitive and demanding tasks, raising the possibility that semantic STM deficits might reflect a problem with control over semantic representations.

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Table 1: Background Details

Group	Case	Sex	Age	Education		Years since CVA	Aphasia type
				(leaving age)	Neuroimaging summary		
Semantic	JB	M	51	15	L temporal (see text)	2	NA
STM	ABU	M	52	15	Non-specific (see text)	4	NA
Semantic Aphasia	JD	M	80	18	NA	9	NA
	NY	M	63	15	L frontal-temporal- parietal	4.5	Conduction
	SC	M	76	16	L occipital-temporal (& R frontal-parietal)	5.5	Anomic/TSA
	PG	M	59	18	L frontal & capsular	5	TSA
	KH	M	73	14	L occipital-temporal & frontal	1.5	Mixed TA
	BB	F	55	16	L frontal & capsular	2.5	Mixed TA
	JM	F	69	18	L frontal-temporal- parietal	6	TSA
	ME	F	36	16	L occipital-temporal	6.5	TSA
	MS	F	73	14	NA	5	Global
	LS	M	71	15	L temporal-parietal- frontal	3	TSA
KA	M	74	14	L frontal-temporal- parietal	1	Global	

TSA = transcortical sensory aphasia. TA = transcortical aphasia. NA = not available. Patients are arranged in order of word-picture matching score (see Table 4). Aphasia classifications were determined using the Boston Diagnostic Aphasia Examination (Goodglass, 1983) and were confirmed by an experienced speech and language therapist.

Table 2: Background neuropsychology

Task	Max	Normal Cut-off	Semantic STM		Semantic Aphasia											
			JB	ABU	Mean	JD	NY	SC	PG	KH	BB	JM	ME	MS	LS	KA
<i>Attentional/Executive</i>																
Raven's progressive matrices ^a	percentiles		<5*	10	-	95	50	50	50	5*	50	5*	<5*	5*	10	5*
WCST (number of categories)	6	-	6	3 [†]	1.1	1*	2*	6	0*	0*	1*	2*	0*	0*	0*	1*
Brixton spatial anticipation (correct) ^b	54	28	28*	30	19.0	28*	34	25*	26*	7*	23*	NT	11*	16*	14*	6*
TEA: counting without distraction	7	5	7	7	4.8	7	3*	7	3*	6	4*	3*	7	NT	3*	NT
TEA: counting with distraction	10	3	10	5	2.6	6	2*	1*	0*	3*	0*	0*	9	NT	2*	NT
<i>Digit Span^c</i>																
Forwards	-	5	7	5	3.8	5	3*	6	6	4*	5	3*	6	0*	4*	0*
Backwards	-	3	4	4	2.0	4	2*	2*	2*	2*	0*	2*	3	NT	1*	NT
<i>Visuospatial</i>																
Rey figure copy ^d	36	29.0	33	29	25.2	31	26*	35	36	NT	20*	NT	9.5*	NT	19.5*	NT
VOSP Incomplete letters	20	17.6	20	19	12.9	20	17*	18	18	19	0*	11*	6*	20	0*	NT
VOSP Dot counting	10	9.5	10	10	8.0	10	10	10	5*	10	10	6*	3*	10	6*	NT
VOSP Position discrimination	20	18.6	20	20	17.5	20	20	17*	20	18	18	16	15*	19	16*	14*
VOSP Number location	10		10	10	8.0	10	10	10	9	9	8	8	2	NT	8	6
VOSP Cube analysis	10	4.7	10	9	5.9	10	5	9	10	3*	2*	4*	4*	8	4*	NT

* denotes impaired scores (>2 standard deviations below normal mean). [†] denotes below 10th percentile. NT = not tested. WCST = Wisconsin Card-Sorting Test (Milner, 1964; Stuss et al., 2000). TEA = Test of Everyday Attention (Robertson et al., 1994). VOSP = Visual Object and Space Perception battery (Warrington & James, 1991). ^a Refers to the standard test for JB and ABU and the coloured test for the remaining patients (Raven, 1962, 1992). ^b Burgess and Shallice (1996). ^c Weschler (1987). ^d Rey (1941).

Table 3: Performance on rhyme and category probe tests

		Semantic Aphasia										Controls ^a		
		JB	ABU	Mean ^a	JD	NY	SC	PG	BB	ME	LS	KA	Mean	SD
Category span		2.7*	2.7*	1.6	1.5*	2.6*	1.7*	1.6*	1.0*	1.3*	<1	<1	6.15	.78
Rhyme span		8.0	6.0	3.0	2.0*	2.4*	1.0*	3.0*	4.3	5.4	<1	<1	6.98	1.54
Single item sorting (%)		94	94	90	83	84	94	92	85	92	67	47		
Category	Length 1	90 (94)	95 (100)		83 (81)	85 (89)	85 (84)	100 (100)	75 (72)	80 (88)	60 (67)	45 (25)		
	Length 2	85 (89)	85 (84)		70 (80)	85 (88)	70 (70)	60 (60)	60 (61)	60 (71)				
	Length 3	71 (77)	71 (67)			67 (70)								
Rhyme	Length 1	100	100		75	80	75	95	100	95	55	60		
	Length 2	95	85		75	80		75	95	75				
	Length 3	100	92		42	67		75	92	79				
	Length 4	92	75					71	88	58 ^b				
	Length 5	90	80						50	85				
	Length 6	81	75							67				
	Length 7	75	61											
	Length 8	75												

* denotes impaired span (modified t-test; $p < .05$). Patient breakdown shows percentage accuracy at each stage of the test and figures in parentheses exclude trials where the target or probe was not sorted correctly. ^a Excludes LS and KA. ^b Testing was continued as this score seemed to be anomalous.

Table 4: Performance on standard semantic battery

Task	Max	Normal Cut-off	Semantic		Semantic Aphasia											
			STM		Mean	JD	NY	SC	PG	KH	BB	JM	ME	MS	LS	KA
			JB	ABU												
<i>64 Item Battery</i>																
Naming	64	59	58*	63	23.5	49*	54*	28*	46*	30*	10*	30*	5*	0*	5*	0*
Word-picture matching	64	62	64	61*	51.0	64	60*	59*	58*	54*	54*	53*	50*	46*	37*	26*
Picture CCT	64	52	59	57	36.1	38*	36*	46*	44*	46*	38*	37*	13*	37*	16*	46*
Word CCT	64	56	62	57	37.2	38*	39*	56*	40*	41*	30*	37*	34*	42*	16*	36*
<i>Environmental Sounds</i>																
Sound-picture	48	36	41	42	27.8	23*	28*	32*	33*	30*	26*	24*	33*	28*	27*	22*
Sound-word	48	33	44	44	25.2	26*	34	32*	25*	26*	27*	16*	35	25*	17*	14*
Word-picture	48	46	48	46*	39.2	46*	44*	41*	47	44*	33*	43*	40*	37*	35*	21*
<i>Boston Naming Test</i> ^a																
Without cueing	60	46 ^b	43*	43*		38*	24*	11*	38*	20*	1*	19*	2*	NT	3*	NT
Additional items named with cue	-	-	9/17	15/17		8/22	19/36	10/49	12/22	6/40	25/59	13/41	14/58	NT	25/57	NT

* denotes impaired scores (below 5th percentile for Boston Naming Test; >2 standard deviations below normal mean for all other tests). CCT = Camels and Cactus Test (Bozeat et al., 2000). ^a Kaplan et al. (1983). ^b Fifth percentile in adults aged 55-65 (Zec, Burkett, Markwell, & Larsen, 2007).

Table 5: Errors in Picture Naming

	JB	ABU	Semantic Aphasia									
			Mean	JD	NY	SC	PG	KH	BB	JM	ME	LS
Percentage of items correct	82	85	36	73	64	31	65	40	10	37	5	6
Error types as a percentage of all errors												
Semantic	45	22	27	56	29	17	52	23	13	23	9	21
Omission	45	61	50	26	53	51	23	68	79	50	85	17
Phonological	0	11	5	0	4	15	9	0	2	12	1	3
Mixed	5	0	5	3	4	9	7	7	3	8	2	0
Other	5	6	13	15	9	7	9	3	3	8	3	59

Table 6: Accuracy and reaction times in speeded semantic tasks

	JB	ABU	Semantic Aphasia				Controls	
			JD	NY	SC	PG	Mean	<i>SD</i>
Picture naming								
Accuracy (%)	71*	90	58*	58*	46*	73*	93	3.7
RT (ms)	5149*	1712*	1222	2692*	9695*	2142*	1038	215
Synonym judgement ^a								
Accuracy (%)	81*	71*	68*	67*	NC	85*	98	2.0
RT (ms)	3802*	2053	12592*	8383*	NC	9103*	1731	288

* denotes impaired performance (modified t-test; $p < .05$). NC = Test not completed. SD = standard deviation. ^a Jefferies et al. (submitted).

Table 7: Verb Generation task

Condition	JB	ABU	Controls	
			Mean	<i>SD</i>
Low selection				
(e.g., apple → eat)				
Accuracy	15/15	11/15	13.8	<i>1.87</i>
Reaction time (ms)	2359	4089	1510	<i>332</i>
High selection-high association				
(e.g., door → open, door → close)				
Accuracy	13/15	10/15	13.9	<i>2.28</i>
Reaction time (ms)	2911	4141	1376	<i>258</i>
High selection-low association				
(e.g., rug → lay, rug → roll)				
Accuracy	8/15	4/15*	13.4	<i>2.95</i>
Reaction time (ms)	3660	6786	2042	<i>708</i>

* denotes impaired accuracy (modified t-test; $p < .05$). SD = standard deviation.

Figure 1: MRI scan for patient JB

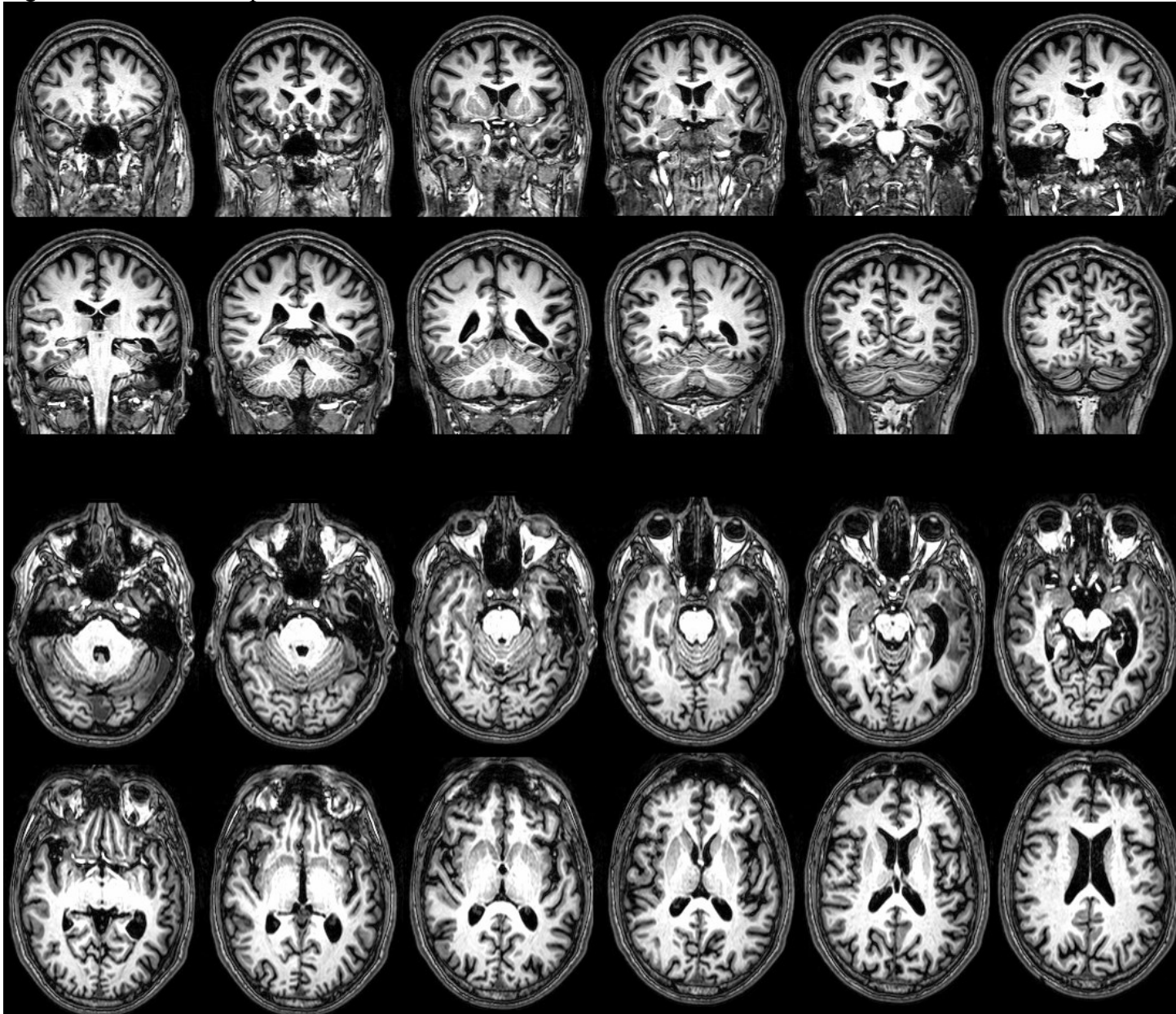
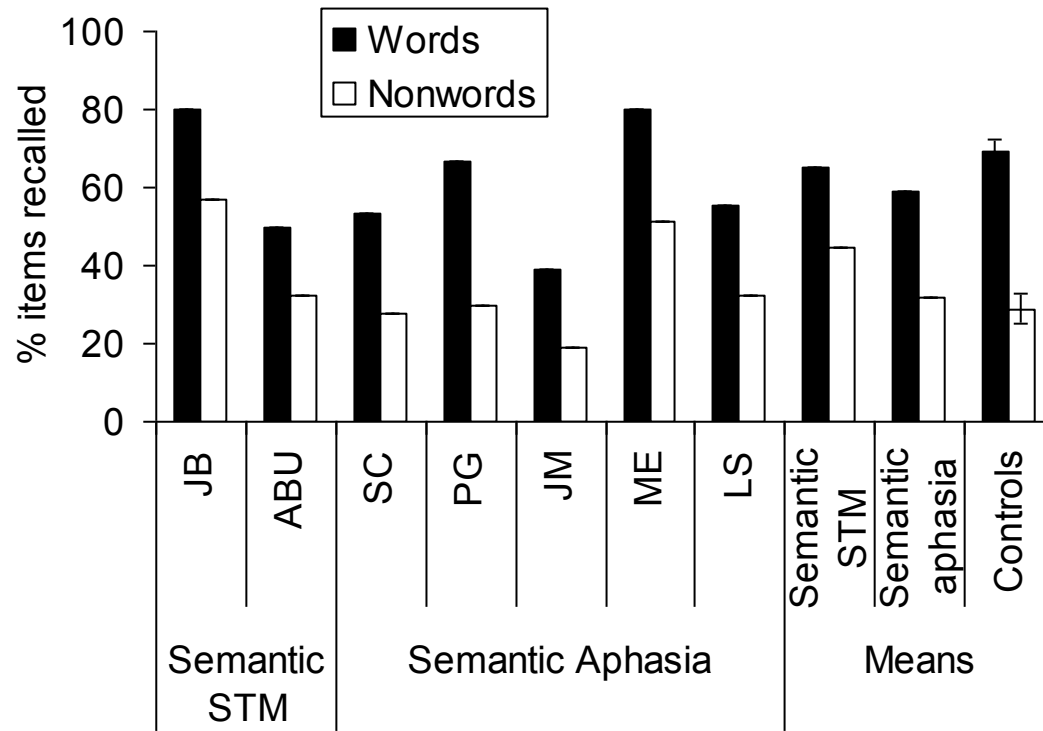


Figure 2: Individual and group data for word and nonword recall



JB, ABU and controls received 4 and 5-item lists; other patients received 2, 3 and 4-item lists. Bars indicate standard error for controls.

Figure 3: Individual and group data for phonological similarity experiment

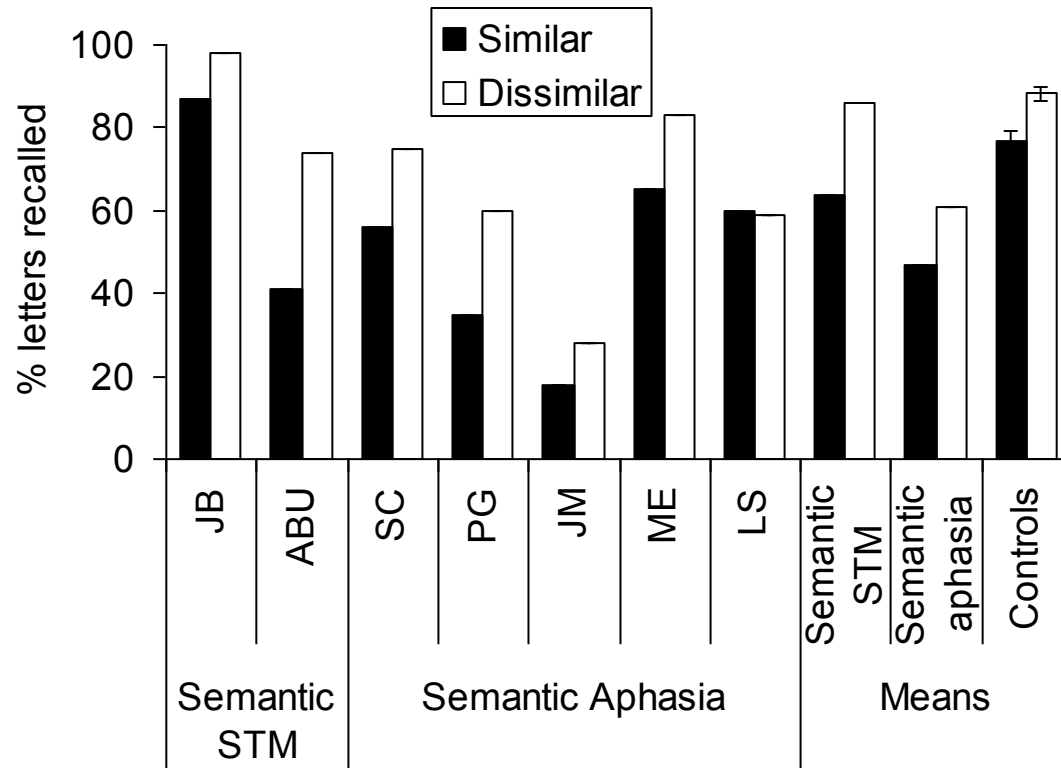
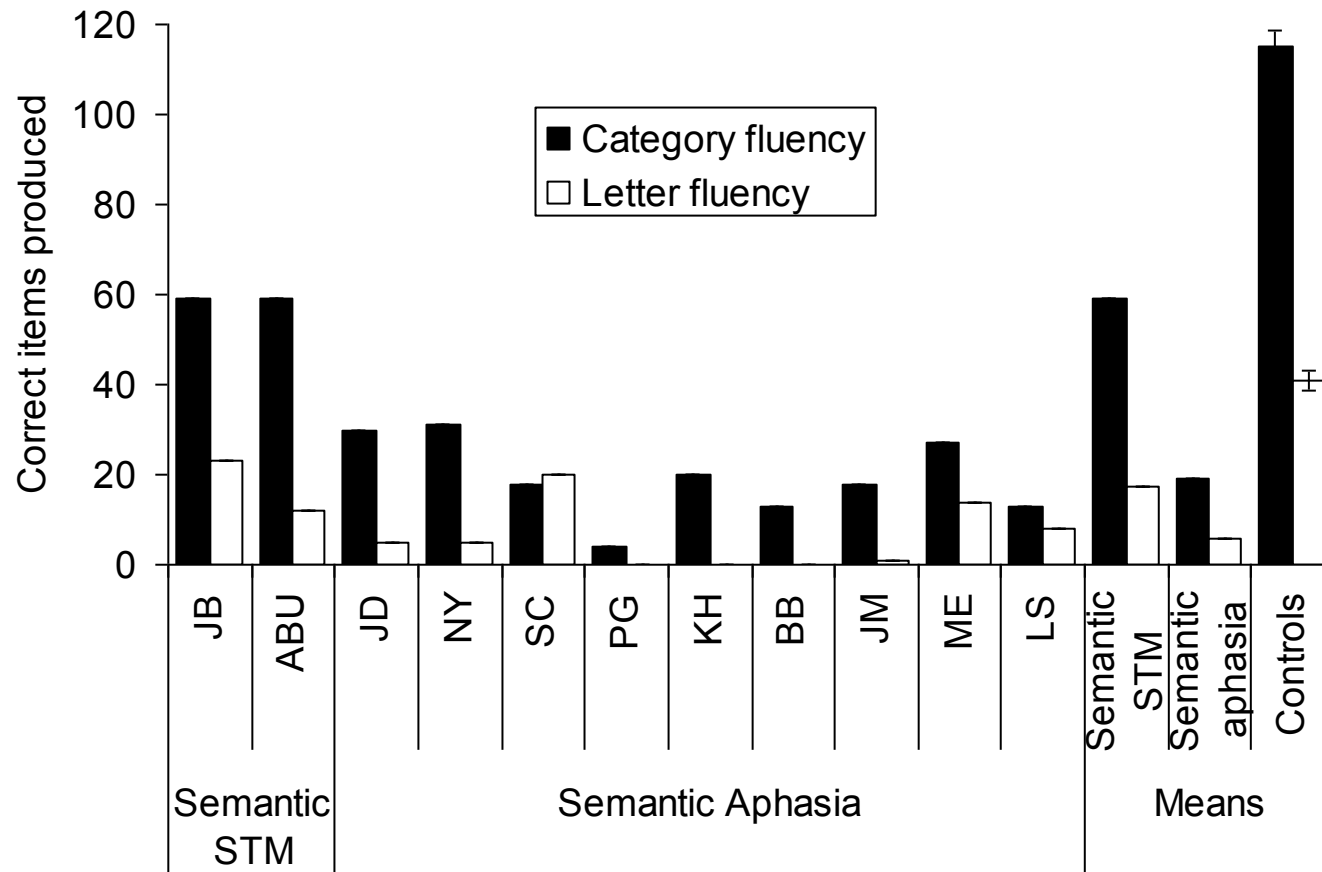


Figure combines data from 4 and 6-item lists, except for PG and JM, who only completed 4-item lists. Bars indicate standard error for controls.

Figure 4: Verbal fluency



Bars indicate one standard error for controls.