ELSEVIER

Neuropsychologia 44 (2006) 2547–2557

NEUROPSYCHOLOGIA

www.elsevier.com/locate/neuropsychologia

Role of the left inferior frontal gyrus in covert word retrieval: Neural correlates of switching during verbal fluency

Elizabeth A. Hirshorn, Sharon L. Thompson-Schill *

University of Pennsylvania, Center for Cognitive Neuroscience, Department of Psychology, 3720 Walnut Street, B-51, Philadelphia, PA 19104, United States

Received 29 July 2005; received in revised form 14 January 2006; accepted 19 March 2006
Available online 24 May 2006

Abstract

Word retrieval ability is commonly assessed with a semantic verbal fluency task, in which subjects must produce a list of exemplars of a category (e.g., animals). The order in which exemplars are produced is not random; rather, subjects tend to produce "clusters" of semantically related items (e.g., cow, pig, sheep) and occasionally "switch" to other clusters (e.g., lion, tiger, bear). Patients with frontal lobe pathology (associated with focal lesions or Parkinson's disease) exhibit reduced output on semantic fluency tasks that has been characterized as a reduction in switching, in contrast to other impaired patient groups who produce normal switches but smaller clusters (e.g., [Troyer, A. K., Moscovitch, M., Winocur, G., Leach, L., & Freedman, M. (1998). Clustering and switching on verbal fluency tests in Alzheimer's and Parkinson's disease. *Journal of the International Neuropsychological Society*, *4*(2), 137–143]). The ability to initiate a switch between two semantic categories may require the selection of weakly activated representations over active (but already reported) representations. Previous studies have shown that increased demands on selection among competing representations are associated with activity in the left inferior frontal gyrus (LIFG) and with deficits in patients with lesions including LIFG [Thompson-Schill, S. L., Jonides, J., Marshuetz, C., Smith, E. E., D'Esposito, M., Kan, I. P., et al. (2002). Effects of frontal lobe damage on interference effects in working memory. *Cognitive Affective & Behavioral Neuroscience*, *2*(2), 109–120; Thompson-Schill, S. L., Swick, D., Farah, M. J., D'Esposito, M., Kan, I. P., & Knight, R. T. (1998). Verb generation in patients with focal frontal lesions: A neuropsychological test of neuroimaging findings. *Proceedings of the National Academy of Sciences of the United States of America*, *26*, 14792–14797]. In the present study, we investigated the neural correlates of switching in the verbal fluency task, and in particular, the role of the LIFG in switching between semantic sub-categories. We observed greater activation in the LIFG during switching compared to free generation (Experiment 1) and self-reported clustering (Experiment 2), which is consistent with the hypothesis that the switching mechanism is subserved by the LIFG due to high semantic selection demands.

Keywords: Prefrontal cortex; Verbal fluency; Speech production; Semantic memory; Cognitive control; Dysexecutive syndrome

Word retrieval in neurologically compromised patients is commonly assessed by asking an individual to produce as many items as possible, in a fixed time period, that meet some criterion (e.g., begin with "F"; member of the category "animals"). Successful performance of this complex *verbal fluency* task likely requires a number of distinct processes ranging from lexical selection and phonetic encoding to working memory and executive control. Not surprisingly then, neuroimaging studies reveal increased activation during verbal fluency in an extensive network of cortical and subcortical regions (Paulesu et al., 1997; Schlösser et al., 1998). Within this network, left prefrontal cortex (PFC) emerges as the site that has been associated with the most extensive and the most consistent impairments on verbal fluency tasks (Janowsky, Shimamura, Kritchevsky, & Squire, 1989; Parks et al., 1988; Perret, 1974). The neural correlates and nature of the left PFC involvement during verbal fluency continue to be studied. A better understanding of the relationship between this region and performance of verbal fluency tasks will contribute to our understanding of the role of the frontal lobes in linguistic and non-linguistic processes.

One strategy for investigating the function of frontal cortex for word retrieval has been to compare different types of verbal fluency tasks. By varying the criterion or rule that participants are instructed to adhere to when retrieving words, putative cog-

* Corresponding author. Tel.: +1 215 573 3536; fax: +1 215 898 1982.
E-mail address: sschill@psych.upenn.edu (S.L. Thompson-Schill).

0028-3932/$ – see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.neuropsychologia.2006.03.035

nitive demands can be manipulated within the context of the verbal fluency paradigm. There are several studies that report differences in the neural systems that support word retrieval in response to a category rule (i.e., semantic fluency) or an initial letter rule (i.e., phonemic fluency): performance on semantic and phonemic fluency tasks can be dissociated both in normal subjects (e.g., under divided attention conditions, Martin, Wiggs, Lalonde, & Mack, 1994), and in comparisons of different forms or loci of brain damage (e.g., frontal lesions disproportionately impact phonemic fluency, Perret, 1974), whereas Alzheimer's disease disproportionately impacts semantic fluency (Rosser & Hodges, 1994; Troster, Salmon, McCollough, & Butters, 1989). Furthermore, semantic and phonemic fluency activate different regions in neuroimaging studies (Mummery, Patterson, Hodges, & Wise, 1996). A number of neuroimaging and neuropsychological studies (cf. Henry & Crawford, 2004; Moscovitch, 1994; Mummery et al., 1996) indicate that semantic fluency is more dependent on temporal lobe regions, whereas phonemic fluency is more dependent on frontal-lobe regions. These dissociations have been attributed to a difference in the retrieval strategies used during semantic and phonemic fluency (e.g., Basso, Burgio, & Pradoni, 1997). However, Baldo and Shimamura (1998) failed to find differences in the impairment of unilateral frontal lobe patients during phonemic and category fluency, advocating that frontal lobes contribute to strategic control and retrieval of lexical-semantic knowledge independent of how it is elicited.

Troyer, Moscovitch, and Winocur (1997) proposed an account of the cognitive processes that underlie verbal fluency that bears on comparisons of phonemic and semantic fluency. Their proposal was based on the following observation: if one inspects the order in which subjects produce items on a verbal fluency task, one will notice "clusters" of semantically related items (e.g., cow, pig, sheep) with occasionally "switches" to other clusters (e.g., lion, tiger, bear). The same applies for phonemic fluency. These two phenomena, they argued, depend on distinct processes that can be selectively disrupted: older healthy adults produced fewer switches than younger healthy control subjects, but normal sized clusters in verbal fluency tasks. Young control subjects produced fewer switches, but normal clusters, during a divided attention task, used to simulate frontal lobe dysfunction, suggesting that only switching is dependant on the frontal lobes (Troyer et al., 1997). They found a more profound decline in switching during the phonemic task than the semantic task, which could be interpreted as a greater need to switch during phonemic fluency, due to a less efficient clustering strategy compared to semantic fluency.

Based on data from patients with focal frontal or temporal lobe lesions, Troyer, Moscovitch, Winocur, Alexander, and Stuss (1998) further proposed that switching is subserved by frontal regions, whereas clustering is subserved by temporal lobe regions; frontal-lobe patients were impaired in switching and temporal-lobe patients were impaired in clustering. Impaired switching has also been reported in patients with frontal-striatal system disorders, such as Parkinson's disease (Troyer, Moscovitch, Winocur, Leach, & Freedman, 1998), and frontal and subcortical system dysfunction, such as HIV/AIDS (Millikin, Trépanier, & Rourke, 2004). Together, these studies provide compelling evidence for a link between frontal cortex and switching behavior; however, the cognitive processes that support switching are as of yet unclear. Troyer, Moscovitch, Winocur, Alexander, et al. (1998) and Troyer, Moscovitch, Winocur, Leach, et al. (1998) suggested that reduced switching in patients with frontal lobe damage may be due to poor initiation or flexibility of search/retrieval processes. Gruenewald and Lockhead (1980) suggest that switching is a search for semantic subcategories. However, others have argued that semantic switching is simply a lack of clustering (Abwender, Swan, Bowerman, & Connolly, 2001). We propose that the ability to initiate a switch between two semantic subcategories may require the selection of weakly activated representations over active (but already reported) representations. Elsewhere, we have argued that the left inferior gyrus (LIFG) is critical for our ability to bias activation patterns in response to conflict that occurs either when a strongly activated representation must be suppressed or when an input fails to constrain representations beyond a weakly activated set of competitors (Thompson-Schill, 2005). These two sources of conflict, referred to as prepotent response override and underdetermined responses, respectively, by Botvinick, Braver, Barch, Carter, and Cohen (2001), create demands for a cognitive control mechanism to bias activation among incompatible representations. Such a mechanism could have the effect of letting one move throughout a semantic space, during performance of a verbal fluency task, out of one local minima (e.g., farm animals) and into another (e.g., pets); in other words, the LIFG may be critical for switching.

Previous studies have shown that increased competition between incompatible representations (and therefore increased demands to bias the selection process) is associated with increased LIFG activity in normal volunteers (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997) and with deficits in patients with lesions including LIFG (Robinson, Blair, & Cipolotti, 1998; Thompson-Schill et al., 2002, 1998). One of the most compelling sources of evidence for this association is provided by Robinson et al. (1998), who described a patient with an LIFG (BA 45) lesion whose verbal planning skills were intact, yet was impaired in generating words in a variety of tasks where the stimuli activated many potential responses as compared to stimuli that only activate a single response. For example, in a sentence completion task, the patient was significantly impaired in generating a phrase to finish a sentence with low response predictability (e.g., "The man ate a sandwich and . . ."), where the possible responses are virtually limitless, compared to a sentence with high predictability (e.g., "The man bought a sandwich and . . .") where the response is most likely "ate it."

A similar effect of competition on language production was observed in a group of patients with LIFG lesions who made significantly fewer errors when asked to retrieve a verb related to a noun with few competing alternatives (e.g., scissors) than to a noun with many competing alternatives (e.g., cat); furthermore, the magnitude of this effect was correlated specifically with the extent of LIFG damage (Thompson-Schill et al., 1998). A group of patients with Alzheimer's disease who exhibited this same competition effect on verb generation, were also more impaired (relative to control subjects) when generating words

beginning with a single letter (e.g., F-) than a two-letter cue (e.g., FL-), and nearly one-third of the patients were able to come up with more words in the latter case than in the former (Tippett, Gendall, Farah, & Thompson-Schill, 2004). Similarly, patients with PFC lesions who were impaired in semantic fluency tasks when the category cue was a large superordinate category (e.g., animals) greatly improved when generating members of a subset of a semantic category (e.g., farm animals) (Randolph, Braun, Goldberg, & Chase, 1993). The difference in performance across these two conditions could be related to the switching impairments reported by Troyer and colleagues (insofar as switches would be more frequent, in control subjects, in large categories than in small ones).

Finally, the association between LIFG and competition among incompatible representations has been established outside the domain of word retrieval as well; for example, increasing conflict between two sources of information (i.e., familiarity and recollection) about the status of a probe on a working memory task, by means of a proactive interference manipulation, is associated with increased LIFG activity (D'Esposito, Postle, Jonides, & Smith, 1999; Jonides, Smith, Marshuetz, Koeppe, & Reuter-Lorenz, 1998) and decreased performance in patients with LIFG damage (Hamilton & Martin, 2005; Thompson-Schill et al., 2002). One such study dissociated these competition effects from response conflict (which was associated with the anterior cingulate cortex rather than left prefrontal cortex; Nelson, Reuter-Lorenz, Sylvester, Jonides, & Smith, 2003). This distinction parallels a dissociation reported with a Stroop task, where prefrontal cortex was associated with conflict among incompatible representations of the stimulus (Milham et al., 2001) rather than response conflict. All of these studies provide a link, albeit in different ways, between LIFG and competition between incompatible representations.

In the present study, we investigated the role of the LIFG – and therefore of the putative cognitive control mechanism it supports – in switching between semantic subcategories produced during a semantic verbal fluency task. We conducted two fMRI experiments that allowed us to examine the relation between LIFG activity and switching during semantic fluency. In Experiment 1, we manipulated the occurrence of switches by instructing subjects either to switch on every trial or to freely generate words in response to a category cue. In Experiment 2, we asked trained subjects to indicate every time a switch occurred while generating words in response to a semantic category cue. It was hypothesized that there would be increased LIFG activity associated with switching in both experiments.

1. Experiment 1

1.1. Participants

Ten paid subjects participated (three males and seven females), mean age 22.8 years. All participants were right-handed, native English speakers (i.e., did not learn another language before age 6 years). Participants were also screened for neurological and neuropsychological illnesses, use of psychoactive medications and learning differences (e.g., dyslexia). Participation consisted of a 1 h session. Participants gave informed consent and were compensated with US$ 20.

1.2. Materials

A total of 40 category names were used in the experiment (see Appendix A). Categories were chosen so that each contained several readily apparent sub-categories, with several possible items in each. For example, the category musical instruments have several possible sub-categories (e.g., string, brass, percussion, woodwinds, etc.) each with many possible items (e.g., violin, viola, cello, trumpet, tuba, saxophone, drum, triangle, xylophone, flute, oboe, clarinet, etc.).

1.3. Procedure

Each participant completed three tasks in a blocked design: two category fluency tasks (free generation and switching) and a non-semantic baseline task. During the free generation task, subjects were asked to generate the names of as many category exemplars as possible in the given time; the instructions were similar to those used in standard semantic fluency tasks. During the switching task, subjects were asked to generate category exemplars such that every item was from a different sub-category as the one previous. Prior to scanning, subjects practiced both conditions, overtly, so that the experimenter could confirm that the switching instructions were clear. During fMRI scanning, subjects retrieved words silently and made a bimanual button press every time they covertly generated an item. Covert fluency tasks have been implemented successfully in order to study fluid verbal fluency in an fMRI scanner (Paulesu et al., 1997; Schlösser et al., 1998). During the non-semantic baseline task, subjects were asked to covertly count backwards by two from a three-digit number. Subjects made a bimanual button press every time they generated a number.

During each trial, the task directions (free generation, switching or counting) were displayed on the screen for 500 ms. The category name or counting instruction was then displayed on the screen for 14.5 s, during which time subjects covertly performed the indicated task. A 2.5 s intertrial interval preceded the next trial. Subjects completed 20 trials (in a fixed, alternating order; e.g., free generation, baseline, switching, baseline, . . .) in each of four data acquisition runs, for a total of 80 trials (20 free generation, 20 switching and 40 baseline). Every subject saw all 40 categories in the same order; however, the assignment of categories to the free generation and switching conditions was counterbalanced across subjects.

Stimuli were rear projected onto a Mylar screen at the head of the scanner with an Epson 8100 3-LCD projector. A mirror was mounted to the head coil to allow subjects to view the screen. PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993) was used to present stimuli using a Macintosh G3 Powerbook laptop.

1.4. Image acquisition

Subjects were scanned at the University of Pennsylvania on a 3 T Siemens Trio scanner using a standard four-channel head

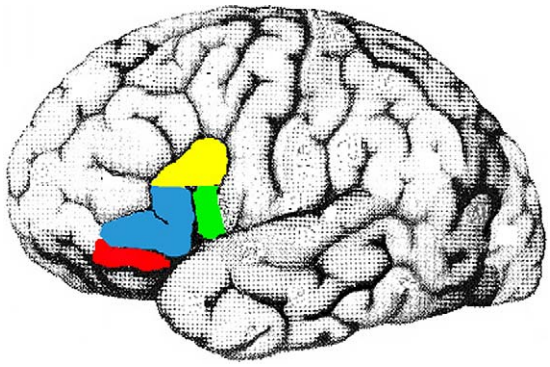

Fig. 1. LIFG sub-region ROIs: red denotes pars orbitalis, blue denotes pars triangularis, green denotes pars opercularis and yellow denotes the dorsal LIFG (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

coil. Foam padding was used to reduce head motion within the coil. For each subject, T1-weighted anatomical scans were performed using a 3D MPRAGE pulse sequence (TR = 1620 ms, TE = 3 ms, TI 950 ms, voxel size = 0.9766 mm × 0.9766 mm × 1 mm, matrix size 192 × 256 × 160) before $T2^*$-weighted functional images were acquired. One hundred and fifty two sets if 45 interleaved, axial gradient echo, echoplanar images were acquired with TR = 2.5, TE = 30, 64 × 64 pixels in a 19.2 cm field of view, voxel size = 3 mm × 3 mm × 4 mm for each run. Prospective motion correction was done online with a PACE sequence.

1.5. Image processing and analyses

Functional images were sinc interpolated in time to correct for the fMRI acquisition sequence. Slices were resampled in time to match the first slice of each volume, and then realigned with respect to the first image of the scan. Images were spatially smoothed with an 8 mm FWHM Gaussian kernel. Data were analyzed using the general linear model as implemented in VoxBo (www.voxbo.org) including an empirically derived 1/*f* noise model, filters that removed low temporal frequencies (0.0125 Hz), regressors to account for global signal variations, and nuisance regressors to account for between-scan differences (Aguirre, Zarahn, & D'Esposito, 1997; Zarahn, Aguirre, & D'Esposito, 1997). Each stimulus condition was modeled as a boxcar function convolved with a canonical hemodynamic response function. Both region of interest (ROI) and whole-brain analyses were performed.

In the ROI analysis, anatomical ROIs were defined in each subject by sulcal boundaries LIFG and subregions: pars orbitalis, pars opercularis, triangularis and the most dorsal region of the IFG defined in the Duvernoy Brain Atlas as F3 (Duvernoy, 1991) (Fig. 1). Two additional ROIs (bilateral superior parietal gyri and anterior cingulate cortex) were also drawn due to possible implications of involvement during task switching (Gurd et al., 2002) or processes involving cognitive control (Cohen, Botvinick, & Carter, 2000; Weiss et al., 2003). Within each anatomically defined ROI, voxels were identified that responded more during semantic fluency trials (free generation and switching) than baseline trials. The responses across these suprathreshold voxels were averaged, resulting in a single time series for each functionally and anatomically defined ROI. For each of these spatially averaged time series, statistical analyses were performed to assess the difference in activation during switching trials versus free generation trials.

In the whole-brain analysis all functional data were normalized to the Montreal Neurological Institute (MNI) using a set of affine transformations with smoothly non-linear deformations, as implemented in SPM2. Functional images were resampled into 3 mm isotropic voxels and spatially smoothed with an 8 mm FWHM Gaussian filter. Individual *t*-maps were calculated for contrasts of interest and then smoothed to 12 mm FWHM to facilitate between-subject averaging before being entered in a random effects analysis. Areas of activation from a random effects analysis were identified at a uncorrected significance level of $p < 0.01$.

1.6. Results

1.6.1. Behavioral results

On average, subjects covertly generated 6.78 (±1.92) items during the switching blocks, 8.98 (±2.94) items during the free generation blocks and 12.38 (±3.14) during the baseline blocks. Subjects made significantly more responses during free generation blocks than switching blocks [$t(9) = 4.22$, $p < 0.01$]. This response rate was comparable to that observed in a group of pilot subjects who performed the task overtly outside of the scanner.

1.6.2. fMRI results

When functionally defining the ROIs, we observed increased activity in all 10 subjects during fluency trials relative to baseline (mapwise, $t > 2.5$) in the LIFG, anterior cingulate and bilateral superior parietal gyri. The comparison of switching and free generation trials within these ROIs revealed significantly greater activity in the LIFG during switching compared to free generation [$t(9) = 3.902$, $p = 0.004$] (see Table 1). More specifically, par triangularis [$t(9) = 3.595$, $p = 0.006$], the most dorsal region of the LIFG [$t(9) = 4.153$, $p = 0.002$] and pars orbitalis [$t(8) = 2.483$, $p = 0.038$] were sensitive to switching compared to free generation. Neither the anterior cingulate nor the bilateral superior parietal gyri ROIs evinced a significant effect of switching.

In an exploratory, whole-brain random effects analysis, the pars triangularis of the LIFG (BA 45) showed greater acti-

Table 1
Mean effect size of switching vs. free generation

Region of interest	Mean effect size
LIFG	$t(9) = 3.90^{**}$
Dorsal LIFG (F3)	$t(9) = 4.15^{**}$
Pars triangularis	$t(9) = 3.60^{**}$
Pars opercularis	$t(9) = 0.16$
Pars orbitalis	$t(8) = 2.48^{*}$
Anterior cingulate	$t(9) = -2.22$
Bilateral superior parietal gyri	$t(9) = 1.27$

$^{*}p < 0.05$ and $^{**}p < 0.01$.

Table 2
Experiments 1 and 2: local maximum activations from group analyses

Brain region (Brodmann area)	Experiment I Switch–free generation	*t*	Experiment I Switch–cluster	*t*
Left				
Superior frontal gyrus (6)	−42, 3, 66	3.26	−12, 21, 63	6.51
Superior frontal gyrus (10)			−30, 54, 18	9.81
Middle frontal gyrus (10/46)	−18, 48,−6	4.05	−51, 45, 9	3.54
Middle frontal gyrus (9)			−54, 21, 39	3.71
Middle frontal gyrus (8)			−33, 18, 51	3.66
Middle frontal gyrus (6)			−39, −3, 51	5.75
Medial frontal gyrus (10)			15, 54, −3	4.89
Inferior frontal gyrus (45)	−39, 24, 18	3.66	−33, 27, 6	9.73
Postcentral gyrus (2)			−39, −24, 33	5.59
Middle temporal gyrus (39)			−33, −63, 21	3.82
Lateral posterior nucleus			−18, −21, 15	3.53
Superior parietal lobule (7)	−3, −57, 63	3.82	−39, −39, 36	7.94
Inferior parietal lobule (40/39)	−57, −57, 54	4.19	−39, −66, 39	5.69
Precuneus (7)	−3, −66, 60	4.99	−12, −66, 51	3.71
Lingual gyrus (18/19)	−3, −72, 0	5.51		
Right				
Superior frontal gyrus (BA 8/9)	48, 24, 54	3.28	39, 45, 39	4.11
Middle frontal gyrus (BA 9)	48, 24, 42	4.23	36, 51, 15	3.84
Middle frontal gyrus (BA 46)	48, 42, 30	3.74		
Middle frontal gyrus (BA 11)	3, 51, −15	5.95		
Inferior frontal gyrus (BA 10)	39, 57, 3	5.53		
Inferior frontal gyrus (BA 47)	36, 42, −9	5.85		
Medial frontal gyrus (BA 8)			15, 33, 48	7.41
Superior temporal gyrus (BA 42)			66, −33, 21	4.11
Inferior temporal gyrus (BA 20)			51, −30, −18	3.61
Claustrum	12, −27, −27	4.41		
Inferior parietal lobule (BA 40)	42, −51, 45	7.34	36, −54, 42	3.94
Cerebellar posterior lobe			48, −60, −33	3.69

vation ($t > 3.25$, $p < 0.01$) during switching blocks than free generation. At this threshold, a number of other regions also exhibited differences between switching and free generation; the local maxima of all regions showing each effect are given in Table 2 (switching–free generation) and Table 3 (free generation–switching).

1.7. Discussion

In Experiment 1, we examined the relation between LIFG activity and switching during verbal fluency by comparing fMRI responses during trials when subjects were explicitly instructed to switch subcategories before each item to those when subjects were not (and therefore would be expected to switch occasionally but not as often). We observed greater activity during the switching blocks than free generation blocks in the LIFG, more specifically the most dorsal region of the LIFG, the pars triangularis and the pars orbitalis. We did not observe the same effect of switching in the anterior cingulate or the bilateral superior parietal gyri. The group analysis supports the hypothesis that the LIFG (BA 45) subserves switching during semantic fluency. As Table 2 indicates, the switching effect in this experiment is not specific to LIFG. However, this analysis revealed the opposite effect in the temporal lobes (bilateral superior temporal lobes, BA 22), which showed more activation across all subjects during the free generation task than the switching task. In light of previous claims about the distinct roles of frontal and temporal cortices in verbal fluency (and semantic retrieval more generally), this result is potentially noteworthy.

Although these results are consistent with the hypothesized role of the LIFG in verbal fluency, there are a number of caveats that must be added to the discussion of these effects. First, we assume that subjects were switching more in the switching trials than in the free generation trials, because in the latter case subjects should be producing clusters as well as switches. However, we have no measure of the number of switches these subjects produced during the free generation trials. Second, we do have a measure of the number of responses made in each condition, and, not surprisingly, subjects retrieved more words during free generation trials than switching trials. Consequently, there are a number of differences between these conditions other than the rate of switching (e.g., number of button pushes). Third, switching trials were likely to be associated with greater demands for processes related to monitoring and evaluating responses than were the unconstrained free generation trials. Because of these confounds, caution is warranted when making inferences about the psychological processes that are related to observed fMRI differences. For this reason, we designed Experiment 2 to allow us to more effectively isolate switching mechanisms.

Table 3
Experiments 1 and 2: local maximum activations from group analyses

Brain region (Brodmann area)	Experiment I Free gen.–switch	*t*	Experiment I Cluster–switch	*t*
Left				
Superior frontal gyrus (BA 10)	−18, 57, 18	5.17		
Medial frontal gyrus (BA 10/11)	−6, 57, 0	3.35	−3, 60, −12	4.36
Anterior cingulate (BA 32)	−3, 36, −3	4.68		
Anterior cingulate (BA 24)	−3, 30, 21	4.63		
Insula (BA 13)	−39, −27, 30	3.36		
Postcentral gyrus (BA 3)	−57, −24, 42	4.11		
Postcentral gyrus (BA 40)	−57,−24, 15	5.59		
Superior temporal gyrus (BA 22)	−45, 0, −3	4.59		
Middle temporal gyrus (BA 21)			−63, 0, −12	3.54
Inferior temporal gyrus (BA 20)				6.09
Inferior parietal lobule (BA 40)	−63, −27, 30	5.52		
Caudate tail			−24, −36, 18	3.47
Parahippocampal gyrus (BA 28)			−21, −24, −9	4.28
Parahippocampal gyrus (BA 36)			−27, −27, −18	4.11
Fusiform gyrus (BA 20)			−30, −42, −24	3.85
Fusiform gyrus (BA 37)			−36, −51, −15	4.79
Fusiform gyrus (BA 19)			−24, −54, −12	10.05
Lingual gyrus (BA 19)			−15, −63, 0	11.75
Lingual gyrus (BA 18)			−6, −75, −9	5.63
Cuneus (BA 17)			−9, −90, 3	3.96
Cuneus (BA 19)			−24, −90, 27	5.03
Middle occipital gyrus (BA 19)	−36, −78, 9	3.75		
Right				
Inferior frontal gyrus (BA 45)	45, 24, 15	4.34		
Medial frontal gyrus (BA 6)	3, −15, 12	4.42		
Precentral gyrus (BA 4)			27, −27, 75	13.29
Cingulate gyrus (BA 23)			3, −33, 30	4.34
Cingulate gyrus (BA 31)			18, −42, 27	10.86
Postcentral gyrus (BA 3)	54, −18, 42	4.84	48, −21, 63	8.98
Insula (BA 13)		3.36	45, −12, 21	3.49
Inferior temporal gyrus (BA 20)			54, −3, −33	4.58
Superior temporal gyrus (BA 42/22)	69, −15, 12	5.63	63, −3, 9	3.57
Superior temporal gyrus (BA 41)	48, −27, 6	5.53		
Uncus (BA 28)			30, −9, −30	6.92
Parahippocampal gyrus			30, −15, −12	4.52
Hippocampus			30, −30, −15	5.76
Fusiform gyrus (BA 19)			39, −66, −12	3.49
Cuneus (BA 19)			12, −78, 30	7.77
Cuneus (BA 17)			9, −96, 3	4.46
Middle occipital gyrus (BA 18)	24, −102, 9	4.23		

2. Experiment 2

2.1. Participants

Nine paid subjects participated (four males and five females), mean age 23.1 years; none of these subjects were in Experiment 1. All participants were right-handed, native English speakers (did not learn another language before age 6 years). Participants were also screened for neurological and neuropsychological illnesses, use of psychoactive medications and learning differences (e.g., dyslexia). Participation consisted of a 1 h session. Participants gave informed consent and were compensated with US$ 20.

2.2. Materials

The same 40 categories from Experiment 1 were used.

2.3. Procedure

Each participant completed two tasks: a semantic fluency task and a non-semantic baseline task. As in Experiment 1, during the baseline task, subjects were asked to covertly count backwards by two from a three-digit number. Subjects made a button press with both thumbs every time they generated a number. During the semantic fluency task, subjects were instructed to generate as many items as possible from a given category in the given time. As in Experiment 1, they were instructed to name the word covertly and to make a button press for every item generated. In this experiment, subjects were to press one button if the item was in the same sub-category as the previous item (i.e., part of a semantic cluster) and another button if the item was in a different sub-category as the previous item (i.e., following a switch). After the experimenter defined clustering and switching and provided examples, subjects practiced six sample categories,

in order to verify their understanding of the instructions, prior to scanning. For example, a possible response for the category "animals" could be: cow, pig, sheep, whale, zebra, dog, cat, squirrel. In this case, the responses would be coded as: cow(n/a), pig(C), sheep(C), whale(S), zebra(S), dog(S), cat(C), squirrel(S) (C = cluster, S = switch). Note that the first item is not coded because we are defining each item by the previous response, and that both clusters and switches may be followed by either a cluster or a switch.

During each trial, the task directions (name or count) were displayed on the screen for 500 ms. The category name (e.g. musical instruments) or counting instruction (e.g., count backwards by 2 from 529) was then displayed on the screen for 14.5 s, during which time subjects performed the indicated task. A 2.5 s intertrial interval preceded the next trial. Subjects alternated between semantic fluency and baseline tasks for 20 trials in each of 4 data acquisition runs, for a total of 80 trials (40 semantic fluency and 40 baseline).

Stimuli were rear projected onto a Mylar screen at the head of the scanner with an Epson 8100 3-LCD projector. A mirror was mounted to the head coil to allow subjects to view the screen. Eprime (Psychology Software Tools Inc.) was used to present stimuli.

2.4. Image acquisition

Image acquisition was identical to Experiment 1.

2.5. Image processing and analyses

Image processing was performed exactly the same as in Experiment 1, with the exception that filters removed low temporal frequencies at and below 0.0209 Hz. During semantic fluency trials, the subjects' behavior was coded every 100 ms as either a cluster, a switch or no response. Each stimulus condition was modeled as a single event and convolved with a canonical hemodynamic response function. First derivative covariates for each condition of interest (clusters and switches) were added to better model each event. The colinearity between the covariate modeling switches and the other covariates of interest was below 0.72 (average = 0.65) in all subjects.

Both region of interest (ROI) and whole-brain analyses were performed. In the ROI analysis, functionally and anatomically defined ROIs were created as in Experiment 1. For each ROI, statistical analyses were performed on the spatially averaged time series, in order to assess the difference in activation during self-reported switching versus self-reported clustering events. The whole-brain analysis was implemented as in Experiment 1.

2.6. Behavioral results

On average, subjects generated 7.58 (±2.04) items per category and self-reported 2.37 (±1.33) items as switches. On average they generated 13.31 items (±2.72) during the baseline task. The latency from one response to the next was shorter preceding a cluster than a switch, [$t(8) = 3.88$, $p < 0.01$]. The mean latency preceding clusters was 1556 (±231 ms) and for switches was 1959 (±351 ms).

Table 4
Mean effect size of self-reported switching vs. self-reported clustering

Region of interest	Mean effect size
LIFG	$t(8) = 3.30^{*}$
Dorsal LIFG (F3)	$t(7) = 3.28^{*}$
Pars triangularis	$t(8) = 4.24^{**}$
Pars opercularis	$t(7) = 2.46^{*}$
Pars orbitalis	$t(6) = 1.43$
Anterior cingulate	$t(3) = 1.59$
Bilateral superior Parietal gyri	$t(7) = 3.88^{**}$

$^{*}p < 0.05$ and $^{**}p < 0.01$.

2.7. fMRI results

As in Experiment 1, we observed increased activity in all nine subjects during fluency trials relative to baseline ($t > 2.5$) in the LIFG. Only four out of nine subjects had increased activation in the anterior cingulate and eight out of nine had increased activation in the bilateral superior parietal gyri. These suprathreshold voxels were used to define the ROIs.

Within the LIFG, activity was greater for switching responses than for clustering responses [$t(8) = 3.301$, $p = 0.011$] (see Table 4). More specifically, pars triangularis [$t(8) = 4.24$, $p = 0.003$], the most dorsal region of the LIFG [$t(7) = 3.28$, $p = 0.013$], and pars opercularis [$t(7) = 2.46$, $p = 0.043$] exhibited a significant switching effect. As can be seen in Fig. 2, by the time the subject pressed the button to indicate whether they had just generated a switch or a cluster, there was already a clear separation between these two response types; this difference was no longer apparent by 7.5 s after the response. This response pattern is what one would expect if the neural event eliciting this BOLD response occurred several seconds prior to the button press; we suggest that this event may be the process that enables switches to occur.

In addition to the switching effects observed in the LIFG, the bilateral superior parietal gyri showed greater activation during switching [$t(7) = 3.875$, $p = 0.006$]. There was no effect

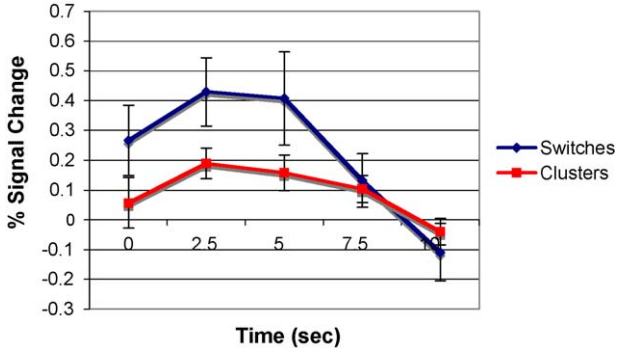

Fig. 2. Average time series of self-reported switches and self-reported clusters in pars triangularis. Time 0 represents the point when the subjects responded with a button press.

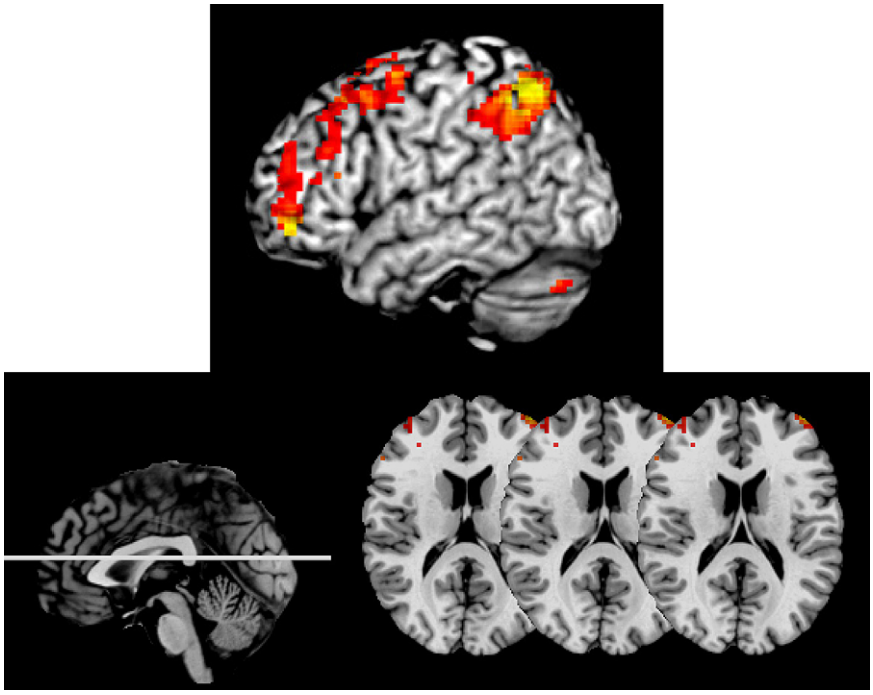

Fig. 3. Activation pattern in conjunction analysis of whole-brain activation in Experiments 1 and 2 at $p < 0.01$. Left lateral view of overlapping activation (top) and axial slices showing LIFG (BA 45) activation (bottom) are shown.

of switching in the anterior cingulate ROI. In an exploratory, whole-brain random effects analysis ($t > 3.356$, $p < 0.01$) the LIFG showed greater activation during switching blocks than free generation. The local maxima of all regions showing a difference between switching and clustering responses at this threshold are given in Table 2 (switching–clustering) and Table 3 (clustering–switching). We also performed a whole-brain conjunction analysis (joint $p < 0.01$) across the two experiments, in order to highlight common regions of activation in both prefrontal and parietal cortices (Fig. 3).

2.8. Discussion

In Experiment 2, we examined the relationship between LIFG and switching during verbal fluency by comparing the fMRI response to self-reported switches and self-reported clustered retrievals. Unlike the switching manipulation we used in Experiment 1, this design allowed us to compare switching and clustering when other task demands (e.g., self-monitoring) were held constant. We observed greater activity during self-reported switches than self-reported clusters in the LIFG, more specifically the most dorsal region of the LIFG, pars triangularis and pars opercularis. We did not observe the same effect of switching in the anterior cingulate; however, in this experiment, the bilateral superior parietal gyri ROI did exhibit a switching effect.

As in Experiment 1, the group analysis supports the hypothesis that the LIFG subserves switching during semantic fluency showing greater activity during self-reported switches than self-reported clusters in pars triangularis, BA 45. The opposite effect was again observed in the in the temporal lobes (bilateral inferior temporal lobes (BA 20), left middle temporal gyrus (BA 21) and right superior temporal gyrus (BA 22)), which showed more activation across all subjects during self-reported clusters than self-reported switches.

3. General discussion

The present findings from Experiments 1 and 2 are consistent with the hypothesis that the LIFG subserves processes that support switching between sub-categories during semantic verbal fluency. Notably, in the group random effects analysis, pars triangularis (BA 45) was more highly activated during switching tasks than free generation (Experiment 1) and self-reported clustering (Experiment 2). Activation in BA 45 has been implicated in tasks where verbal responses to stimuli activate many potential responses (Robinson et al., 1998), thus having to select among many alternatives in order to respond (Kan & Thompson-Schill, 2004a). The finding of switching effects in the LIFG in Experiment 2 helps to discount the possibility that the difference in the response between switching and free generation tasks in Experiment 1 was due to self-monitoring (or other task confounds) alone. Another limitation of Experiment 1 was that we assumed, but could not verify, that subjects produced more switches when instructed to than when freely generating responses. By comparing the number of switches reported in Experiment 2 (under free generation instructions) to the number of responses produced in Experiment 1 in the switching condition, we can more confidently assert that our task instructions in Experiment 1 had the desired affect of manipulated switching frequency.

We observed switching-related activation throughout much of the extent of the inferior frontal gyrus across the two experiments. However, the subregion of the LIFG that was consistently activated in both experiments was the pars triangularis (BA 45). The location of this effect may be relevant for current

speculation about the functional–anatomical organization of the LIFG. In particular, Badre, Poldrack, Paré-Blagoev, Insler, and Wagner (2005) have argued for a theoretical distinction between mechanisms they refer to as "postretrieval selection" and "controlled retrieval", and they claim that the former is subserved by the mid-LIFG (pars triangularis) whereas the latter is subserved by the anterior-LIFG (pars orbitalis). The more posterior region, according to the authors, is sensitive to competition from incompatible (but active) representations while the more anterior region reflects a controlled retrieval process that is necessitated only by insufficient activation of a representation (such as might occur when trying to evaluate a weak association between two words). Although, we find some flaws with the notion, implicit in this distinction, that competition would not *also* arise in the context of insufficient activation from a bottom-up source, we agree that the functional–anatomical dissociation the authors report is in need of some parsimonious explanation (e.g., it may reflect the distinction between prepotent response override and underdetermined responding, two situations that both create conflict among incompatible representations). Although, we suspect that switching during verbal fluency is an event that could, in principle, require any or all of these putative processes, it may be the case that the more dorsal (BA 45) switching-related activation pattern we observed will ultimately be informative for this continuing discussion.

Although the focus of this study was on the hypothesized link between the LIFG and switching, our exploratory whole-brain analysis yielded a few results that warrant additional comment. Note that we are focusing here on effects that were consistent across the two experiments. We consider these regions to be the most likely candidates for involvement in the mechanisms that support switching (or conversely, clustering in the reverse contrast). Three such regions that emerged reliably across the two experiments, in addition to the LIFG, were the left middle frontal gyrus (LMFG) and bilateral parietal cortex (greater during switching than clustering) and bilateral temporal cortex (greater during clustering than switching).

In a recent review of over 31 neuroimaging studies of shifts of attention, bilateral parietal cortex (inferior, superior and medial) consistently emerges as a locus of activation (Wager, Jonides, & Reading, 2004). Although many of the studies in their review concerned shifts of visual or spatial attention, it is possible that the same types of mechanisms that bias activation during visual processing are deployed when shifting attention in conceptual space (Kan & Thompson-Schill, 2004b). For this reason, we defined an a priori ROI in bilateral parietal cortex. Switching effects were significant in this ROI only in Experiment 2, although the exploratory whole-brain analyses suggest parietal involvement during switching in both experiments. It is likely that multiple cognitive processes support switching during verbal fluency; future studies may be able address differences between LIFG and parietal contributions to switching that are not evident with the current experimental designs.

Another region that exhibited switching effects (in the exploratory, whole-brain analyses) in both experiments was the left middle frontal gyrus. There are a number of neuroimaging studies that have reported increased activation that extends throughout lateral PFC (including inferior and middle frontal gyri) in response to demands to select among incompatible, competing representations (e.g., Jonides et al., 1998). In fact, at least one study reported a similar effect centered in the LMFG, not the LIFG: in an early fMRI study, Desmond, Gabrieli, and Glover (1998) observed more fMRI activation in LMFG when subjects retrieved a word in response to a word stem that could be completed with many possible words (e.g., STA-) compared to stems that could be completed with only a few words (e.g., PSA-). The activation loci reported in the LMFG were on or close to the inferior frontal sulcus, centered on the dorsal bank (in the LMFG) instead of the ventral bank (LIFG). In the present study, the LMFG activation is directly on the dorsal bank of the inferior frontal sulcus in Experiment 1 (anterior to 45/47) and Experiment 2 (anterior to BA 45). Given recent reports of extreme variability in sulcal boundaries between two cytoarchitecterally defined Brodmann's areas in PFC (Amunts et al., 1999, 2004), it is not clear to what extent these variable localization patterns represent functional variability or anatomical variability across subjects. At present, we can simply conclude that processes related to switching during verbal fluency engage LIFG and LMFG regions in ventrolateral PFC.

In contrast to all of the effects described thus far, there is consistently more temporal lobe activation during clustering than switching. The nature of the increased temporal lobe activity during clustering could be due to temporal inhibition during switching, or simply because more items were produced during clustering than switching. We do not aim to make strong claims concerning the nature of the temporal lobe activity during clustering. Nevertheless, the collective results from Experiments 1 and 2 supports the proposal put forth by Troyer et al. (1997), Troyer, Moscovitch, Winocur, Alexander, et al. (1998) and Troyer, Moscovitch, Winocur, Leach, et al. (1998) that the frontal lobes mediate switching, whereas the temporal lobes mediate clustering during fluency tasks. These results suggest that in addition to being dissociable behaviorally (Troyer et al., 1997), clustering and switching engage different neural networks in normal controls.

4. Summary

Numerous studies have shown ventrolateral PFC involvement during a variety of verbal (Kan, Caravella, & Thompson-Schill, 2005; Thompson-Schill et al., 2002, 1998) and non-verbal tasks (Brandon, Hirshorn, Jha, Fabian, & Thompson-Schill, 2004) where performance requires overriding a highly activated representation or selecting among weakly activated, incompatible representations. We propose that switching during verbal fluency is another instance of a response that depends on a domain-general mechanism that is needed to guide selection among competing representations. These data support this hypothesis by linking switching to activity in the LIFG, a region that has been associated with a putative control mechanism in numerous studies. Further investigation is needed to access whether the generality of this effect (both to other types of verbal fluency, such as phonemic fluency, and to other types of non-verbal, gen-

erative tasks), as well as to probe the differences between frontal and parietal contributions to switching in this context.

Acknowledgements

This research was supported by NIH RO167008 and the Searle Scholars Program. A preliminary version of this study was reported at the annual Human Brain Mapping meeting in 2004. We would like to thank Geoffrey K. Aguirre, Julia C. Lemos and J. Stephen Higgins for their help in the design and analysis of this study. Correspondence regarding this manuscript should be addressed to Sharon L. Thompson-Schill, Department of Psychology, University of Pennsylvania, 3720 Walnut Street B-51, 19104.

Appendix A. Categories

US states (example/instructions)
Colors (practice)
Shapes (practice)
Things bought in a grocery store (practice)
Books (practice)
Things that have wheels (practice)
School supplies (practice)

1. Animals
2. Appliances
3. Beverages
4. Cars
5. Cleaning products
6. Clothing
7. College majors
8. Colleges/universities
9. Cosmetics
10. Countries
11. Diseases/illnesses
12. Drugs/medications
13. Famous people
14. Fruits
15. Furniture
16. Games
17. Gems/stones
18. Hobbies
19. Holidays
20. Insects
21. Island
22. Jobs
23. Junk Food
24. Languages
25. Magazines
26. Modes of transportation/vehicle
27. Movies
28. Musical instruments
29. Musicians/music artists
30. Parts of the body
31. Plants
32. Religions
33. Sandwiches
34. Sports
35. Television programs
36. Things that fly
37. Toiletries
38. Tools
39. US presidents
40. Vegetables

References

Abwender, D. A., Swan, J. G., Bowerman, J. T., & Connolly, S. W. (2001). Qualitative analysis of verbal fluency output: Review and comparison of several scoring methods. *Assessment*, *8*(3), 323–336.

Aguirre, G. K., Zarahn, E., & D'Esposito, M. (1997). Empirical analyses of BOLD fMRI statistics. II. Spatially smoothed data collected under null-hypothesis conditions. *Neuroimage*, *5*(3), 199–212.

Amunts, K., Schleicher, A., Burgel, U., Mohlberg, H., Uylings, H. B., & Zilles, K. (1999). Broca's region revisited: Cytoarchitecture and intersubject variability. *Journal of Comparative Neurology*, *412*(2), 319–341.

Amunts, K., Weiss, P. H., Mohlberg, H., Pieperhoff, P., Eickhoff, S., Gurd, J. M., et al. (2004). Analysis of neural mechanisms underlying verbal fluency in cytoarchitectonically defined stereotaxic space: The roles of Brodmann areas 44 and 45. *Neuroimage*, *22*, 42–56.

Badre, D., Poldrack, R. A., Paré-Blagoev, E. J., Insler, R. Z., & Wagner, A. D. (2005). Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. *Neuron*, *47*, 907–918.

Baldo, J. V., & Shimamura, A. P. (1998). Letter and category fluency in patients with frontal lobe lesions. *Neuropsychology*, *12*(2), 259–267.

Basso, A., Burgio, F., & Pradoni, P. (1997). Semantic category and initial letter word fluency in left-brain-damaged patients. *European Journal of Neurology*, *4*, 544–550.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Reviews*, *108*(3), 624–652.

Brandon, M., Hirshorn, E. A., Jha, A. P., Fabian, S., & Thompson-Schill, S. L. (2004). Proactive interference resolution during nonverbal working memory: Evidence for domain-general processing in LIFG. In *Poster session presented at the annual meeting of the cognitive neuroscience society*.

Cohen, J. D., Botvinick, M., & Carter, C. S. (2000). Anterior Cingulate and prefrontal cortex: Who's in control? *Nature Neuroscience*, *3*(5), 421–423.

Cohen, J. D., MacWhinney, B., Flatt, M., & Provost, J. (1993). PsyScope: A new graphic interactive environment for designing psychology experiments. *Behavioral Research Methods, Instruments, and Computers*, *25*(2), 257–271.

Desmond, J. E., Gabrieli, J. D., & Glover, G. H. (1998). Dissociation of frontal and cerebellar activity in a cognitive task: Evidence for a distinction between selection and search. *Neuroimage*, *7*(4 Pt 1), 368–376.

D'Esposito, M., Postle, B. R., Jonides, J., & Smith, E. E. (1999). The neural substrate and temporal dynamics of interference effects in working memory as revealed by event-related functional MRI. *Proceedings of the National Academy of Sciences of the United States of America*, *96*(13), 7514–7519.

Duvernoy, H. (1991). *The human brain: Surface, three dimensional anatomy, and MRI*. New York: Springer-Verlag.

Gruenewald, P. J., & Lockhead, G. R. (1980). The free recall of category examples. *Journal of Experimental Psychology: Human Learning and Memory*, *6*, 225–240.

Gurd, J. M., Amunts, K., Weiss, P. H., Zafiris, O., Zilles, K., Marshall, J. C., et al. (2002). Posterior parietal cortex is implicated in continuous switching between verbal fluency tasks: An fMRI study with clinical implications. *Brain*, *125*, 1024–1038.

Hamilton, A. C., & Martin, R. C. (2005). Dissociations among tasks involving inhibition: A single-case study. *Cognitive Affective & Behavioral Neuroscience*, *5*(1), 1–13.

Henry, J. D., & Crawford, J. R. (2004). Meta-analytic review of verbal fluency performance following focal cortical lesions. *Neuropsychology*, *18*(2), 284–295.

Janowsky, J. S., Shimamura, A. P., Kritchevsky, M., & Squire, L. R. (1989). Cognitive impairment following frontal lobe damage and its relevance to human amnesia. *Behavioral Neuroscience*, *103*(3), 548–560.

Jonides, J., Smith, E. E., Marshuetz, C., Koeppe, R. A., & Reuter-Lorenz, P. A. (1998). Inhibition in verbal working memory revealed by brain activation. *Proceedings of the National Academy of Sciences of the United States of America*, *95*(14), 8410–8413.

Kan, I. P., Caravella, R. A., & Thompson-Schill, S. L. (2005). Effects of frontal lobe damage on verbal fluency and picture naming. In *Paper presented at the Cognitive Neuroscience Society*.

Kan, I. P., & Thompson-Schill, S. L. (2004a). Effect of name agreement on prefrontal activity during overt and covert picture naming. *Cognitive, Affective & Behavioral Neuroscience*, *4*(1), 43–57.

Kan, I. P., & Thompson-Schill, S. L. (2004b). Selection among perceptual and conceptual representations. *Cognitive Affective & Behavioral Neuroscience*, *4*, 466–482.

Martin, A., Wiggs, C. L., Lalonde, F., & Mack, C. (1994). Word retrieval to letter and semantic cues: A double dissociation in normal subjects using interference tasks. *Neuropsychologia*, *32*(12), 1487–1494.

Milham, M. P., Banich, M. T., Webb, A., Barad, V., Cohen, N. J., Wszalek, T., et al. (2001). The relative involvement of anterior cingulate and prefrontal cortex in attentional control depends on nature of conflict. *Cognitive Brain Research*, *12*, 467–473.

Millikin, C. P., Trépanier, L. L., & Rourke, S. B. (2004). Verbal fluency component analysis in adults with HIV/AIDS. *Journal of Clinical & Experimental Neuropsychology*, *26*(7), 933–942.

Moscovitch, M. (1994). Cognitive resources and dual-task interference effects at retrieval in normal people: The role of the frontal lobes and medial temporal cortex. *Neuropsychology*, *8*(4), 524–534.

Mummery, C. J., Patterson, K., Hodges, J. R., & Wise, R. J. (1996). Generating 'tiger' as an animal name or a word beginning with T: Differences in brain activation. *Proceedings of the Royal Society of London—Series B: Biological Sciences*, *263*(1373), 989–995 [published erratum appears in Proc R Soc Lond B Biol Sci 1996 Dec 22;263(1377):1755–6].

Nelson, J. K., Reuter-Lorenz, P. A., Sylvester, C. C., Jonides, J., & Smith, E. E. (2003). Dissociable neural mechanisms underlying response-based and familiarity-based conflict in working memory. *Proceedings of the National Academy of Science*, *100*, 11171–11175.

Parks, R. W., Loewenstein, D. A., Dodrill, K. L., Barker, W. W., Yoshii, F., Chang, J. Y., et al. (1988). Cerebral metabolic effects of a verbal fluency test: A PET Scan Study. *Journal of Clinical & Experimental Neuropsychology*, *10*(5), 565–575.

Paulesu, E., Goldacre, B., Scifo, P., Cappa, S. F., Gilardi, M. C., Castiglioni, I., et al. (1997). Functional heterogeneity of left inferior frontal cortex as revealed by fMRI. *NeuroReport*, *8*, 2011–2016.

Perret, E. (1974). The left frontal lobe of man and the suppression of habitual responses in verbal categorical behavior. *Neuropsychologia*, *12*, 323–330.

Randolph, C., Braun, A. R., Goldberg, T. E., & Chase, T. N. (1993). Semantic fluency in Alzheimer's, Parkinson's, and Huntington's disease: Dissociation of storage and retrieval failures. *Neuropsychology*, *7*(1), 82–88.

Robinson, G., Blair, J., & Cipolotti, L. (1998). Dynamic aphasia: An inability to select between competing verbal responses? *Brain*, *121*(Pt 1), 77–89.

Rosser, A., & Hodges, J. R. (1994). Initial letter and semantic category fluency in Alzheimer's disease, Huntington's disease, and progressive supranuclear palsy. *Journal of Neurology, Neurosurgery & Psychiatry*, *57*(11), 1389–1394 [see comments].

Schlösser, R., Hutchinson, M., Joseffer, S., Saarimaki, A., Stevenson, J., Dewey, S. L., et al. (1998). Functional magnetic resonance imaging of human brain activity in a verbal fluency task. *Journal of Neurology, Neurosurgery & Psychiatry*, *64*, 492–498.

Thompson-Schill, S. L. (2005). Dissecting the language organ: A new look at the role of Broca's area in language processing. In A. Cutler (Ed.), *Twenty-first century psycholinguistics: Four cornerstones* (pp. 173–189). Hillsdale, NJ: Lawrence Erlbaum Associates.

Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National Academy of Sciences of the United States of America*, *94*(26), 14792–14797.

Thompson-Schill, S. L., Jonides, J., Marshuetz, C., Smith, E. E., D'Esposito, M., Kan, I. P., et al. (2002). Effects of frontal lobe damage on interference effects in working memory. *Cognitive Affective & Behavioral Neuroscience*, *2*(2), 109–120.

Thompson-Schill, S. L., Swick, D., Farah, M. J., D'Esposito, M., Kan, I. P., & Knight, R. T. (1998). Verb generation in patients with focal frontal lesions: A neuropsychological test of neuroimaging findings. *Proceedings of the National Academy of Sciences of the United States of America*, *26*, 14792–14797.

Tippett, L. J., Gendall, A., Farah, M. J., & Thompson-Schill, S. L. (2004). Selection ability in Alzheimer's disease: Investigation of a component of semantic processing. *Neuropsychology*, *18*(1), 163–173.

Troster, A. I., Salmon, D. P., McCollough, D., & Butters, N. (1989). A comparison of category fluency deficits associated with Alzheimer's and Huntington's disease. *Brain and Language*, *37*, 500–513.

Troyer, A. K., Moscovitch, M., & Winocur, G. (1997). Clustering and switching as two components of verbal fluency: Evidence from younger and older healthy adults. *Neuropsychology*, *11*(1), 138–146.

Troyer, A. K., Moscovitch, M., Winocur, G., Alexander, M. P., & Stuss, D. (1998). Clustering and switching on verbal fluency: The effects of focal frontal- and temporal-lobe lesions. *Neuropsychologia*, *36*, 499–504.

Troyer, A. K., Moscovitch, M., Winocur, G., Leach, L., & Freedman, M. (1998). Clustering and switching on verbal fluency tests in Alzheimer's and Parkinson's disease. *Journal of the International Neuropsychological Society*, *4*(2), 137–143.

Wager, T. D., Jonides, J., & Reading, S. (2004). Neuroimaging studies of shifting attention: A meta-analysis. *Neuroimage*, *22*, 1679–1693.

Weiss, E. M., Siedentopf, C., Hofer, A., Deisenhammer, E. A., Hoptman, M. J., Kremser, C., et al. (2003). Brain activation pattern during a verbal fluency test in healthy male and female volunteers: A functional magnetic resonance imaging study. *Neuroscience Letters*, *352*, 191–194.

Zarahn, E., Aguirre, G. K., & D'Esposito, M. (1997). Empirical analyses of BOLD fMRI statistics. I. Spatially unsmoothed data collected under null-hypothesis conditions. *Neuroimage*, *5*(3), 179–197.