Differential processing of thematic and categorical conceptual relations in spoken word production

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Abstract

Studies of semantic context effects in spoken word production have typically distinguished between categorical (or taxonomic) and associative relations. However, associates tend to confound semantic features and/or morphological representations, such as whole-part relations and compounds (e.g., BOAT-anchor, BEE-hive). Using a picture-word interference paradigm and functional magnetic resonance imaging (fMRI), we manipulated categorical (COW-rat) and thematic (COW-pasture) TARGET-distractor relations in a balanced design, finding interference and facilitation effects on naming latencies, respectively, as well as differential patterns of brain activation compared to an unrelated distractor condition. While both types of distractor relation activated the middle portion of the left middle temporal gyrus (MTG) consistent with retrieval of conceptual/lexical representations, categorical relations involved additional activation of posterior left MTG, consistent with retrieval of a lexical cohort. Thematic relations involved additional activation of the left angular gyrus. These results converge with recent lesion evidence implicating the left inferior parietal lobe in processing thematic relations, and may indicate a potential role for this region during spoken word production.

Keywords: semantic knowledge, thematic relations, spoken word production
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Studies of semantic context effects in speech production have typically distinguished between categorical (or taxonomic) and associative relations. In the former, stimuli are members of the same category (e.g., animal) and are usually coordinates (e.g., mouse and fox) that share visual or structural features (such as fur and four legs), while in the latter the conceptual relationship is more heterogeneous (e.g., mouse and cheese). For example, associative relationships may be reflected in the co-occurrence of items in language use, or in normative output of free-association to lexical cues (e.g., Alario, Segui, & Ferrand, 2000; Sailor et al., 2009), or defined operationally as words drawn from a common semantic frame of reference or theme (e.g., Abdel Rahman & Melinger, 2007). Categorical and associative relationships produce different context effects in the picture-word interference (PWI) paradigm, in which target pictures to be named are paired with distractor words to be ignored (Rosinski, Golinkoff, & Kukish, 1975). Compared to distractor words unrelated to the target picture name, categorically related distractors slow naming responses when presented at short stimulus onset asynchronies (SOAs; -200 ms [distractor first] to +150 ms [picture first]), an effect termed semantic interference (SI; see Levelt, Roelofs & Meyer, 1999). By contrast, associate distractors facilitate naming responses at predominantly early SOAs (-450 ms to -100 ms, [distractor first]; e.g., Alario et al., 2000; La Heij, Dirkx, & Kramer, 1990; Lupker, 1979; Sailor et al., 2009).

The different effects observed for associatively and categorically related distractors in the PWI task are of key importance to current models of lexical selection in speech production. In these models, processing between representational
levels is typically accomplished by spreading activation (see Dell & Sullivan, 2004; Goldrick, 2007). The SI effect observed with categorically related distractors has traditionally been interpreted as evidence for lexical selection by competition (LSC; e.g., Goldrick, 2007; Levelt et al., 1999). According to this account, activation spreads to the target and related concepts at the conceptual level, and then on to the corresponding lexical representations. The categorically related distractor increases the activation level of an existing lexical competitor to the target picture’s name, thereby slowing selection of the appropriate response. However, LSC accounts have not typically imposed limits on the spread of conceptual-to-lexical activation for different types of semantic relations, and SI appears restricted to categorical relations between distractor and target in PWI (see Mahon et al., 2007). Aside from associates, facilitation effects have also been reported for whole-part semantic relationships between target and distractor (e.g., Costa, Alario, & Caramazza, 2005).

In order to explain the observed facilitation effects for semantic relationships within an LSC account, Abdel Rahman and Melinger (2009) recently proposed that all distractors semantically related to the target induce both conceptual/lexical priming and lexical competition. According to this explanation, unless a cohort of lexical competitors is activated via converging activation of the conceptual features shared within a category and thus category members, the net result is facilitation. When a cohort is activated, the additional competition changes the net result to interference. Abdel Rahman and Melinger (2009a) termed this a “swinging lexical network” account of SI. Other recent explanations of associative facilitation in PWI have similarly emphasised conceptual priming in the absence of lexical competition (e.g., La Heij, Kuipers & Starreveld, 2006). The post-lexical PWI account of Caramazza and colleagues (Costa et al., 2005; Mahon et al., 2007; Miozzo &
Caramazza, 2003) assumes that distractor words have a privileged relationship with the articulators, and enter an output buffer as phonologically well-formed responses. Further, conceptual/lexical priming is assumed to occur for both associative and categorical relations, with the SI effect arising from an additional response bottleneck at the level of the output buffer, due to categorically related items sharing some response-relevant criteria. According to this account, as associate distractors do not fulfill response-relevant criteria, they do not produce SI.

Unfortunately, the available evidence for a conceptual priming account of associative facilitation in PWI is complicated by confounds with shared semantic features and/or morphological representations, such as whole-part relations and compounds. For example, Alario et al.’s (2000) and Sailor et al.’s (2009) associative stimuli, although selected according to published free association norms, included TARGET-distractor pairings with whole-part relations and/or potential compound words (e.g., BOAT-anchor, DOOR-handle; BEE-hive; APPLE-pie). Abdel Rahman and Melinger’s (2007; Experiment 3) PWI study in which associates were defined contextually likewise included whole-part relations, with photographs of target nationalities to be named paired with distractor-words referring to the headgear that the depicted individuals were wearing (e.g., RUSSIAN-ushanka, FRENCHMAN-beret, ARABIAN-turban). These confounds likely have a boosting influence on the facilitation effect reported for associates in PWI studies. For example, Costa et al. (2005) demonstrated facilitation in PWI for items with part-whole relations that were not technically associates (e.g., EAGLE-talon), while Dohmes, Zwitserlood, and Bölte’s (2004) PWI study demonstrated facilitation for compound distractors with either semantically transparent or opaque relationships to the target picture.
Aside from lexicalized compounds and part-whole relations, associates can reflect thematic conceptual relations. These latter relations are determined by the performance of complementary roles in the same context or event (see Estes, Golonka & Jones, 2011). For example, mouse and cheese are related by an eating/consuming theme. Relatively few studies have explicitly examined thematic relations in spoken word production (e.g., Abdel Rahman & Melinger, 2007, 2011), and fewer still have examined their neural correlates. Using the same stimuli as Abdel Rahman and Melinger (2007; Experiment 3), Aristei, Melinger, and Abdel Rahman (2011) reported an electrophysiological study in which categorical and thematic relations were contrasted in a hybrid blocked cyclic naming and PWI paradigm with auditory distractors. They found temporally overlapping effects for thematic and categorical relations with similar topographical distributions over posterior temporal lobe sites, though differing in polarity. Schwartz et al. (2011) used voxel-based lesion symptom mapping (LSM) in aphasic patients to demonstrate dissociable anterior temporal and inferior parietal lobe (angular gyrus) regions underlying picture naming errors coded as categorically and thematically related, respectively, once the variance attributable to the other error-type was removed. These authors proposed that processing thematic relations involves the additional simulation or retrieval of event representations in areas such as the inferior parietal lobe (IPL) and posterior middle temporal gyrus (MTG) to create a ‘momentary linkage’ between the target concept and others performing a role in the same context.

By contrast, categorical relations in spoken word production have been the subject of more extensive neuroimaging investigation, with at least three fMRI studies examining the SI effect in PWI and reporting varying results. For example, de Zubizarrai et al. (2001) reported an fMRI study in which pictures were superimposed
with either written distractor words or non-lexical control items (a row of Xs), finding increased activity in left middle and posterior temporal regions for the categorically related pairs. Abel et al. (2009) employed auditory distractors at an early -200 ms SOA and failed to find any significant differences in activity between categorically related and unrelated distractors, although they did find increased activity for a comparison of associatively related and unrelated distractors in the left angular gyrus of the IPL and mid-portion of the left MTG. A direct comparison of associatively and categorically related conditions revealed significantly increased activity for the former distractors in left mid-MTG. However, according to the authors, approximately a third of their associative target-picture pairings comprised whole-part relations, with the remainder described as comprising “situational” relations (Abel et al., 2009, p. 1117). Significant reductions in activity in left middle and posterior temporal regions were reported for categorically related versus unrelated distractors in another fMRI study that presented auditory distractors and pictures simultaneously (de Zubicaray & McMahon, 2009). It is worth noting that the reports of differential middle and posterior temporal lobe activity have been interpreted as supporting a lexical level explanation of the SI effect, based upon the Indefrey and Levelt (2004) meta-analysis that attributed roles for these regions in conceptual/lexical (lemma) and phonological word form retrieval, respectively (see Dell & Sullivan, 2004; Indefrey, 2011).

In the present study, we employed the PWI paradigm in an fMRI experiment to provide converging behavioural and neuroimaging evidence for the level(s) at which thematically and categorically related distractor effects occur in spoken word production, and to test rival lexical and post-lexical level accounts of semantic facilitation and interference, as these accounts make contrasting predictions concerning the brain regions engaged by these effects (e.g., Abdel Rahman &
Melinger, 2009a; La Heij et al., 2006; Mahon et al., 2007). While all accounts assume semantic facilitation and interference involve conceptual/lexical processing that might be expected to engage left anterior and middle temporal cortical regions as noted above, the post-lexical account (e.g., Costa et al., 2005; Dhooge & Hartsuiker, 2010; Mahon et al., 2007) predicts additional selective activation for the SI effect in regions supporting motor-articulatory processing and verbal self-monitoring, corresponding to the left premotor and supplementary motor areas (SMA), and bilateral superior temporal gyri (STG; see Indefrey, 2011; Price, 2010; also Alario et al., 2006; Peeva et al., 2010; Tremblay & Gracco, 2009). For example, a recent fMRI study reported differential activity in these regions for the distractor frequency effect in PWI, a finding interpreted as supporting a post-lexical account (de Zubicaray et al., 2012; Miozzo & Caramazza, 2003). The findings of Abel et al. (2009), Schwartz et al. (2011) and Aristei et al. (2011) provide additional evidence for the involvement of IPL regions (especially the angular gyrus) in processing of thematic/associative relations compared to categorical relations in picture naming. Hence, it seems reasonable to expect differential activity in these regions for this contrast in the present experiment.

We implemented a novel, balanced design in which the same written distractor words were used in all three conditions (thematically and categorically related versus unrelated), paired with different target pictures. The advantage of this design is that it precludes alternate explanations for any differences in processing between conditions in terms of distractor properties. A sparse temporal sampling fMRI sequence was employed that avoids the motion-related artefacts associated with overt speech production in fMRI experiments using continuous imaging (see Gracco, Tremblay &
Pike, 2005), one that has been applied successfully to investigate a range of PWI effects (e.g., Heim et al., 2008).

**Method**

**Participants**

Twenty healthy participants (18 female, \( M_{\text{age}} = 21.25 \) years, age range 18-27 years) performed the experiment. All were undergraduate students of the University of Queensland who were reimbursed AUD$30 for participating. All were right-handed native English speakers, with no history of neurological or psychiatric disorder, substance dependence, or known hearing deficits. All had normal or corrected-to-normal vision and gave informed consent in accordance with the protocol approved by the Medical Research Ethics Committee of the University of Queensland.

**Materials**

Thirty-six black-and-white line drawings of common objects served as targets, and 36 words served as distractors in each of three conditions. Pictures were selected from the set provided by Cycowicz, Friedman, and Rothstein (1997) or were of similar style downloaded from the internet via Google images. Each picture was paired with three different words in a balanced design by rearranging target-distractor pairings to create the experimental conditions: a thematically related word, a categorically related word and an unrelated word (see the Appendix for a list of the picture and word stimuli). None of the related pairings were phonologically related, nor were any synonyms or homophones. None comprised part-whole relations or
potential compounds. Although many thematically related concepts are not
associated, and vice versa (see Estes et al., 2011), we did index the bidirectional
strength of associative pairings using free association indices from the University of
South Florida Free Association Norms (Nelson, McEvoy, & Schreiber, 2004) and
Edinburgh Associative Thesaurus (Kiss et al., 1973) where available. Each thematic
pairing was assigned a score according to the proportion of times the associated target
word was produced as a response to the cue, as this was the only metric common to
both norms used. Thematically related pairings had an average forward association
score of 0.12. Reversing the associative relationship, our associative stimuli had an
average backward association score of 0.14. Average association scores in either
direction for the categorically related and unrelated conditions were all zero (i.e., the
cue-target and target-cue pairings did not appear in either the Edinburgh or South
Florida norms).

**Apparatus**

A Dell Vostro laptop PC running Microsoft VisualBasic and ExacTicks (Ryle
Design) software was used to deliver the picture and word stimuli and record vocal
responses on digital audio files (sampling rate 11 kHz). Line drawings were presented
in black on a luminous white background, and the visual distractor words were shown
in red lowercase Times New Roman 18-point bold font in the centre of each picture.
Stimuli back-projected using a BenQ SL705X projector onto a screen which the
participants viewed through a mirror mounted on the head coil. The size of the
pictures including background was approximately 10 cm wide by 10 cm high, and
subtended approximately 10° of visual angle when each participant was positioned for
imaging. A 30 db attenuating headset was used to reduce gradient noise. Naming
responses were recorded on digital audio files using a custom positioned fibre-optic
dual-channel noise-cancelling microphone attached to the head coil (FOMRI-III,
Optoacoustics Ltd., Or-Yehuda, Israel; http://www.optoacoustics.com). Naming
latencies were determined automatically with voice-key software custom written in
Microsoft VisualBasic, and verified manually using Audacity software
(http://audacity.sourceforge.net) in case non-vocal noise triggered the voice key.

Procedure

A PWI paradigm was employed. Following positioning in the scanner,
participants were first familiarised with the set of experimental pictures with the
appropriate label printed below. Over two consecutive practice blocks they were
instructed to name the pictures as fast and as accurately as possible. Erroneous
naming responses were corrected. In a final block, they viewed the pictures without
labels and were instructed to name the pictures per the instructions above.

One hundred and eight trials were presented (36 target pictures presented in
each of three distractor conditions: thematically related, categorically related, and
unrelated), split equally across two blocks of 54 trials. A short break was permitted
between the two blocks while a structural image was acquired (see image acquisition
below). Trial presentation was pseudorandomised across participants using Mix
software (van Casteren & Davis, 2006) such that two presentations of the same
picture were always interceded by at least five different pictures, and presentation of
the distractor conditions was counterbalanced according to the order of the distractor
across participants. Five different pseudorandomisations were employed (each
administered to 4 participants). Participants were instructed to name the pictures as
quickly and accurately as possible while ignoring the distractor. They were instructed
not to speak or move during image acquisition and in the event of a naming error not to correct their response. Trial presentation involved the following sequence: A fixation point (+) was shown for 50 ms, followed by the presentation of the distractor word at an SOA of -150 ms and the target picture. Distractor and picture remained on the screen for 375 ms and 750 ms respectively.

**Image acquisition.** A Bruker Medspec 4T system with a transverse electromagnetic (TEM) head coil for radiofrequency transmission and reception (Vaughn et al., 2002) was used to acquire the data. Functional T2*-weighted images depicting BOLD contrast (64 x 64 matrix; 3.6 x 3.6 mm voxels) were acquired with a gradient echo echo planar imaging (EPI) sequence optimised for both image quality and noise reduction (McMahon, Pringle, Eastburn & Mailet, 2004). A point-spread function (PSF) mapping sequence was acquired prior to the EPI data to correct geometric distortions (Zaitsev, Hennig, & Speck, 2003). Two blocks of 55 image volumes of 36 axial 3.5 mm slices (0.1 mm gap) were acquired (effective repetition time, 15 s; echo time, 30 ms; flip angle, 90°). A sparse temporal sampling sequence was applied to capture the estimated peak BOLD signal response to task-related neural activity (Eden et al., 1999; Elliott, Bowtell, & Morris, 1999). For each trial, no field gradients were applied for a 4 s period of relative silence allowing for stimulus presentation and the participant’s overt verbal response. A single image volume was then acquired within 3 s, approximately coincident with the trial’s estimated peak BOLD response. No field gradients were applied for an additional 8 s period to allow the BOLD response to the gradient noise to return to baseline (for a diagram of the imaging protocol, see Figure 1 in de Zubicaray et al., 2001). Head movement was limited by foam padding within the head coil. A 3D T1-weighted structural image was then acquired using a magnetisation prepared rapid acquisition gradient echo
sequence (MPRAGE; 256$^3$ matrix; 0.9 mm$^3$ voxels). Total imaging time was approximately 50 minutes.

**Image analysis.** Data preprocessing and analysis were conducted with statistical parametric mapping software (SPM8; Wellcome Department of Imaging Neuroscience, Queen Square, London, UK). The first volume in each fMRI block was discarded, and the remaining images were motion corrected using the INRIAlign toolbox (Freire, Roche, & Mangin, 2002). A mean image was generated from the realigned series, and coregistered to the T1-weighted image. The T1-weighted image was next segmented using the ‘New Segment’ procedure. The ‘DARTEL’ toolbox (Ashburner, 2007) was then employed to create a custom group template from the segmented grey and white matter images and individual flow fields were used to normalise the realigned fMRI volumes to the MNI atlas T1 template. The images were resampled to 3 mm$^3$ voxels and smoothed with a 9 mm FWHM isotropic Gaussian kernel to accommodate the relatively lower SNR associated with sparse acquisitions, following Nebel et al. (2005). Global signal effects were then estimated and removed using a voxel-level linear model (Macey et al., 2004). In a final step, the images from each distractor condition were regrouped to comprise a single epoch and errors assigned to a separate condition (see Behavioural data section below).

We conducted a two-stage, mixed effects model statistical analysis. Epoch types corresponding to the distractor and error conditions were modelled as effects of interest with delta functions representing each epoch onset, and convolved with a basis function consisting of a single finite impulse response (FIR) corresponding to a boxcar function that encompassed the epoch length. As the sparse image sequence does not acquire BOLD time course information, trials were not convolved with a conventional haemodynamic response function (HRF; see Eden et al., 1999; Elliott et
al., 1999; Gracco et al., 2005). Linear contrasts were applied to each participant’s parameter estimates at the fixed effects level, then entered in a group level random effects repeated measures analysis of variance (ANOVA) in which covariance components were estimated using a restricted maximum likelihood (REML) procedure to correct for non-sphericity (Friston et al., 2002). Planned $t$-contrasts were employed within the SPM8 random effects design matrix to identify regions showing significant differences in activity between the three experimental conditions.

As we had a priori hypotheses concerning specific neuroanatomical regions associated with various processing stages involved in speech production, we opted to first restrict voxel-wise analyses to a set of predefined regions of interest (ROIs; Figure 1) via small volume corrections (SVC), thereby controlling for multiple comparisons only in those voxels, using labeled maximum likelihood maps from 3D probabilistic atlases. The majority of these were selected from the Hammers et al. (2003) probabilistic atlas: left IPL and anterior temporal cortex (regions involved in thematic and categorical speech errors identified by Schwartz et al., 2011), mid- and posterior temporal cortices (regions identified by the Indefrey & Levelt, 2004 meta-analysis associated with lexical-conceptual selection and phonological word form retrieval), and bilateral STG (verbal self-monitoring according to the Indefrey & Levelt, 2004 meta-analysis). The left premotor cortex ROI was selected from the Eickhoff et al. (2005) cytoarchitectonic atlas as it encompassed the stereotactic MNI co-ordinates reported by both Alario et al., (2006) and Tremblay and Gracco (2010) for their SMA regions involved in post-lexical selection, as well as the ventrolateral premotor area implicated in articulation in Indefrey and Levelt’s (2004) meta-analysis.
It is important to note that the ROIs from the probabilistic atlases represent only close approximations to the descriptive macroanatomical labels reported in the Indefrey and Levelt (2004; also Indefrey, 2011) meta-analysis for regions associated with various processing stages (e.g., left posterior middle and superior temporal gyri for phonological word form retrieval). As the selected ROIs generally encompassed larger regions (e.g., the left posterior temporal cortex ROI from the Hammers et al. 2003 atlas also includes the posterior inferior temporal gyrus), we employed SVC as our hypotheses typically concerned a subset of voxels within each ROI, rather than the mean activity across all voxels (see Poldrack, 2007). However, by estimating SVC thresholds from all voxels within the larger ROI, this approach produces a more conservative threshold for controlling type 1 error.

A height threshold of \( p < .001 \) was adopted in conjunction with spatial cluster extent thresholds of \( p < .05 \) (family-wise error [FWE] corrected) established independently for each ROI using an estimate of the probability of false positive (noise-only) clusters (determined via the smoothness of the image of the residuals from the random effects analysis, i.e., \( \sqrt{\text{ResMS}} \), masked with each ROI) using a Monte Carlo estimation procedure with 10,000 simulations (3dFWHMx and 3dClustSim, implemented in Analysis of Functional NeuroImages toolkit, AFNI; National Institute of Mental Health, Bethesda, MD). In addition to the ROI analyses with SVC, we conducted an exploratory, unrestricted whole-brain analysis to identify activity in regions not predicted a priori, using an identical height threshold in conjunction with a spatial cluster extent threshold of 32 voxels to keep the FWE rate at \( p < .05 \) across the whole brain, determined via the Monte Carlo estimation procedure described above.
Results

Behavioural data.

Data from three participants were excluded from all analyses due to excessive head movement during image acquisition, defined as motion exceeding one voxel (3 mm) within a single imaging block. Trials on which the remaining 17 participants committed errors or dysfluencies (i.e., incorrect/omitted responses or stuttered) were excluded from analysis (17 or 2.7%). Additional trials were excluded in which naming onset reaction times (RTs) were < 250 ms and > 2000 ms (5 or 0.8%). Mean naming RTs as a function of distractor condition are given in Table 1. Repeated measures ANOVAs were conducted for RTs in the three distractor conditions with $F_1$ treating participants as a random factor, and $F_2$ treating items as a random factor. Due to the low error rates, these were not subjected to analysis. These revealed a significant main effect of condition, $F_1(2, 32) = 13.23$, $MSE = 717.87$, $p < .001$, $\eta^2 = .45$ and $F_2(2, 70) = 8.36$, $MSE = 2540.624$, $p < .005$, $\eta^2 = .19$. Planned contrasts (one-tailed paired $t$-tests) revealed significantly faster naming RTs for thematically related compared to unrelated distractors $t(16) = -1.91$, $p < .05$, $d = -.46$. Pictures paired with categorically related distractors were named more slowly than those paired with unrelated words $t(16) = 3.38$, $p < .005$, $d = .82$. Finally, pictures paired with thematically related distractors were named significantly faster than those paired with categorically related words $t(16) = -4.676$, $p < .001$, $d = -1.13$. 
Imaging data.

**A priori defined ROI analyses.** The \( t \)-contrast of thematically related < unrelated distractor conditions revealed significant activity in the left mid-MTG using SVC with the left middle temporal cortex ROI (Table 2 and Figure 2). No significant activity was observed in the remaining ROIs using SVC for this contrast. In addition, no significant activity was observed for the reverse contrast (thematically related > unrelated) using SVCs with any of the ROIs.

The \( t \)-contrast of categorically related < unrelated conditions revealed significant activity in several of the a priori defined ROIs using SVC, including the left middle temporal (mid-MTG) and posterior temporal cortices (pMTG), and premotor cortex (Table 2 and Figure 3). No significant activity was identified in the left ATL or IPL using SVC for this contrast. In addition, no significant activity was observed for the reverse contrast (categorically related > unrelated) using SVCs with any of the ROIs.
Using SVC, significant activity was identified in the left IPL (angular gyrus as above) and middle temporal lobe (mid-MTG) ROIs (Figure 4) for the \( t \)-contrast of thematically related > categorically related conditions. No significant activity was observed in the remaining ROIs using SVC for this contrast. In addition, no significant activity was observed for the reverse contrast (thematically < categorically related) using SVCs with any of the ROIs.

**Unrestricted whole brain analyses.** The \( t \)-contrast of thematically related < unrelated distractor conditions revealed significant activity in two large clusters encompassing bilateral occipital and parietal lobe regions using correction for multiple comparisons at the whole brain level (Table 2 and Figure 2). No significant activity was observed for the reverse contrast (thematically related > unrelated).

The \( t \)-contrast of categorically related < unrelated conditions revealed significant activity in bilateral occipito-parietal and premotor/supplementary motor areas and in the left mid-MTG using correction for multiple comparisons at the whole brain level (Table 2 and Figure 3). No significant activity was observed for the reverse contrast (categorically related > unrelated).

The \( t \)-contrast of thematically related > categorically related conditions revealed significant activity in the left angular gyrus and right SMA using correction for multiple comparisons at the whole brain level. No significant activity was observed for the reverse contrast (thematically < categorically related).

-----Insert Figure 4 about here-----

**Discussion**
The present study examined the effects – both neural and cognitive – of manipulating the thematic and categorical relatedness of distractor words on picture name production. This manipulation differed from prior PWI studies investigating associative relatedness by excluding the potentially confounding influences of whole-part relations and morphological representations, and by employing a balanced design in which the same distractors were paired with different pictures from the target set to create the experimental conditions. A robust interference effect was observed for the naming latencies in the categorically related condition, with a facilitation effect observed for thematically related distractors, compared to an unrelated distractor condition. The former effect entailed significant reductions in activity in hypothesized left middle and posterior portions of the MTG and in left SMA, while the latter effect involved reductions in activity primarily in the left middle MTG. A direct comparison of the two related distractor conditions revealed significantly increased activity in the left middle MTG and angular gyrus, and right SMA for thematically related items.

The finding of relatively faster naming latencies for thematically related compared to unrelated target-distractor pairings represents to our knowledge the first direct evidence for this type of conceptual relation selectively influencing spoken word production. The mean facilitation effect observed (-16 ms) was comparable to the PWI facilitation effects reported for associates at the same (e.g., -21 ms, Sailor et al., 2009, Exp. 1) or earlier SOAs (e.g., -39 ms at -200 ms SOA, Abel et al., 2009; -35 ms at -234 ms SOA; Alario et al., 2000; -25 ms at -300 ms SOA, Sailor et al., Exp. 2). As noted in the Introduction, at least part of the facilitation effect observed for associates may reflect the confounding contributions of semantic feature-based and/or morphological priming (e.g., Costa et al., 2005; Dohmes et al., 2004). The facilitation
effect for thematic relations occurred in conjunction with a significant reduction in activity in left middle MTG, a region having been hypothesised a priori based upon neuroimaging evidence indicating a role in conceptual/lexical (lemma) processing (see Indefrey, 2011). The available electrophysiological data indicates lemma retrieval is accomplished ~200 to 250 ms post-target presentation in left mid-MTG, although the duration may vary according to the type and extent of conceptual processing required by a task (Indefrey, 2011; Strijkers & Costa, 2011). For example, using a go-nogo paradigm Abdel Rahman and Sommer (2003) showed that retrieval occurs relatively later for peripheral conceptual information such as the food an animal prefers to eat compared to information about animacy or size. This may explain why facilitation effects for TARGET-distractor pairings such as MOUSE-cheese are typically observed at early negative SOAs.

A robust SI effect (+30 ms) was observed for categorically related compared to unrelated distractors, consistent with much previous research (see Levelt et al., 1999). Two distinct peaks of significantly reduced activity were observed in left mid- and posterior-MTG for this contrast, consistent with the foci observed in an earlier fMRI study employing written distractors (de Zubicaray et al., 2001). Although the original findings were interpreted as evidence for cascaded rather than serial processing between lemma and phonological word form levels, Indefrey (2011) recently offered the alternate explanation that the posterior temporal cortex activation more likely reflected word reading in the categorically related condition compared to the non-lexical control condition employed in that study (a row of Xs). That explanation is unlikely to be applicable to the present results. The reduced activity compared to the unrelated condition is also consistent with the findings of a previous PWI study of SI employing auditory distractors (de Zubicaray & McMahon, 2009).
The fact that thematic facilitation and SI were both associated with reductions in fMRI activity in the present study has implications for the nature of the processing architecture(s) responsible for PWI effects. Prior electrophysiological and fMRI studies have reported neural responses of identical polarity for phonological facilitation (in which the target picture is paired with a distractor matched for the initial phoneme, e.g., DOG-doll) and SI effects elicited in the same experiment. These effects have been attributed to target excitation and distractor inhibition processes, respectively, matching those proposed in cascaded-interactive spreading activation models of spoken word production (see Dell’Acqua et al., 2010; de Zubicaray & McMahon, 2009). Although Aristei et al. (2011) reported electrophysiological results of opposite polarity for associative facilitation and SI effects over posterior temporal regions, the reliability of this result has been questioned recently by Janssen, Carreiras and Barber (2011). They noted the polarity of the semantic effect in Aristei et al.’s study was opposite to their own findings with a blocked cyclic naming task and those reported by several previous studies (e.g., Dell’Acqua et al., 2010; Jescheniak et al., 2002, 2003). They suggested this discrepancy might be due to Aristei et al.’s (2011) use of a complex design entailing a combination of blocked cyclic naming and PWI, and post-hoc analyses based on selected subsets of participants (only those commencing the experiment with the unrelated condition) and items (only those that were repeated).

It is also possible that the signal reductions observed in the related conditions might reflect a repetition suppression effect given that participants had been familiarized with the picture stimuli multiple times prior to the experiment, and the pictures were presented three times subsequently across distractor conditions. For example, Abel et al. (2009) employed novel sets of colour pictures across distractor
conditions in their variation of the PWI procedure, reporting signal increases for their contrast of associatively related and unrelated distractor conditions in an ROI analysis. However, as the present design involved a counterbalanced presentation of target pictures across distractor conditions, such that the ordinal positions of the pictures in each condition were approximately matched across participants, we consider a repetition suppression effect unlikely.¹ It is worth noting that employing novel sets of pictures across distractor conditions introduces confounds in terms of variations in perceptual characteristics (e.g., form, texture, colour) and semantic features determining subordinate and superordinate category memberships that may influence base naming latencies across conditions and interact with distractor relatedness, perhaps resulting in signal increases (e.g., Abel et al., 2009).

Given that onsets for middle- and posterior-MTG activity are typically observable between 200 and 360 ms post-stimulus presentation and are attributed to lexical-level processes of lemma retrieval and word form encoding, respectively (Indefrey, 2011; Strijkers & Costa, 2011), the current finding of differential activity in the latter region solely for the comparison of categorically related and unrelated conditions could be viewed as reflecting the activation of a lexical cohort at the word form level, consistent with the swinging lexical network proposal of Abdel Rahman and Melinger (2009a). According to this proposal, while both thematically and categorically related conditions entail conceptual priming, only the latter involves activation of a lexical cohort that induces competition due to activation of shared features within a category and thus category members. As thematic relations do not involve shared feature activation, a lexical cohort is not elicited and facilitation is observed. Of note, Whitney, Jefferies, and Kircher (2011) have recently provided
fMRI evidence implicating pMTG in competition during retrieval of words with multiple versus single meanings.

The swinging lexical network proposal has been challenged by the proponents of the post-lexical account (Mahon & Caramazza, 2009; but see the response by Abdel Rahman & Melinger, 2009b). The post-lexical account likewise proposes both related conditions involve conceptual priming, however, it makes no prediction concerning differential lexeme/word form level activation for categorically related distractors (see Costa et al., 2005; Mahon et al., 2007). Nonetheless, the additional finding of reduced activity in the left SMA for the SI effect is difficult for a lexical-level explanation to accommodate, as SMA activity typically commences 400 to 600 ms post stimulus presentation and tends to be interpreted in terms of the initiation of motor-articulatory responses (e.g., Indefrey, 2011; Peeva et al., 2010; Price, 2010; Tremblay & Gracco, 2009). One way of reconciling the SMA result with the lexical-level explanation is to assume it merely reflects the later initiation of target name responses in the categorically related condition. Alternatively, both early middle-MTG and later SMA results could be deemed consistent with separate conceptual/lexical priming and post-lexical decision mechanisms operating on production-ready representations in an articulatory buffer (Mahon et al., 2007), although the finding of posterior-MTG activity attributable to lexeme level activation remains problematic. Miozzo and Caramazza (2003) proposed a similar post-lexical account of the distractor frequency effect in PWI, with Dhooge and Hartsuiker (2010) invoking the verbal self-monitor as the decision mechanism. Although a recent fMRI study of the distractor frequency effect revealed differential activity in the left SMA, this activity extended laterally and ventrally throughout premotor and motor cortices, with additional extensive involvement of bilateral STG, the overall pattern being
interpreted in support of the post-lexical account (de Zubicaray et al., 2012). Neither of the latter regions showed differential activity in the present study, despite the use of a priori defined ROIs for small volume corrections. Consequently, a conservative interpretation of the above results is that they do not permit either account of the SI effect to be falsified, and might also indicate that a model incorporating aspects of both accounts may be more viable (de Zubicaray et al., 2012). Such an account might involve a model architecture like that proposed recently by van Maanen, van Rijn, and Borst (2009). Their model assumes that interference is distributed over multiple stages of processing, with lexical selection being either the dominant process or a subprocess according to the nature of the stimuli employed and the task instructions.

The direct contrast of thematically and categorically related conditions in the present study revealed significantly increased activity for the former distractors in left middle-MTG, angular gyrus (AG) in the IPL, and the SMA. The latter peak may reflect either the difference in time taken to initiate a naming response between the two conditions, or the engagement of a decision mechanism operating on a response bottleneck in the categorically related condition (e.g., Mahon et al., 2007). Abel et al. (2009) likewise reported differential left middle-MTG activity for associative versus categorical relations in their fMRI study that included some target-distractor pairings with ‘situational’ relations. Given the reliable role in conceptual/lexical processing ascribed to the left middle-MTG region, this differential activity between the two types of conceptual relations may represent the processing demands of retrieving the more peripheral thematic relations (e.g., Abdel Rahman & Sommer, 2003; Indefrey, 2011). In a recent update to the Indefrey and Levelt (2000; 2004) meta-analysis of neuroimaging data, Indefrey (2011) noted a probable though unclear role for the IPL in spoken word production. Combined with recent lesion evidence implicating the
angular gyrus in thematically related naming errors (Schwartz et al., 2011), the present results are consistent with a role for the IPL in processing thematic relations during spoken word production (e.g., Indefrey, 2011). This role requires further exploration, and we suggest a potential approach below.

The precise role of the AG in processing thematic relations and role of the IPL in speech production more generally have been subject to speculation. Schwartz et al. (2011) proposed the left AG/IPL involvement in thematic relations might reflect simulation or retrieval of event representations, based on a consideration of evidence linking sensorial and motor experiences with objects that was offered in support of embodied theories of conceptual processing (e.g., Kalénine et al., 2009). An alternative view that does not involve an assumption of a direct role in conceptual processing for the IPL (embodied or otherwise) involves the uncontroversial proposal that language and verbal short term memory (STM) representations are shared (e.g., Martin, Lesch, & Bartha, 1999), with attention able to be allocated to separable item or serial order information as required (see Acheson & MacDonald, 2009; Majerus, 2009). As thematic relations are reflected in lexically co-occurring items definable in terms of the performance of complementary roles in the same context or event (see Estes et al., 2011), accessing or retrieving them is likely to involve a critical component of order information that is not typical of categorical relationships. Importantly, this novel hypothesis is readily testable – patients with relatively greater proportions of thematic speech errors should therefore show relatively larger impairments in order STM, as item and order STM appear to be doubly dissociable in patients with aphasia (e.g., Attout et al., 2012). As we did not include a specific manipulation of order STM in the present experiment, we cannot infer that the IPL
activation we observed for the contrast of thematic > categorical relations was due to this mechanism. Rather, we offer this hypothesis for testing in future studies.

One final result that deserves mention is the differential activity observed in bilateral extrastriate visual cortices for comparisons of both related versus unrelated conditions in the whole brain analyses. As all depicted objects and distractor words were matched across conditions, an explanation in terms of automatic activation of object images associated with the words’ referents seems unlikely. An intriguing possibility is that the result reflects word meaning-dependent modulation of early processing stages in object recognition as has been reported in some recent studies (occurring around 120 ms; e.g., Rabovsky, Sommer, & Abdel Rahman, 2012). This explanation appears consistent with the negative 150 ms distractor SOA employed in the present study, and the absence of differential extrastriate visual cortex activation when both related conditions were compared directly. Hence, this result may also be considered consistent with the operation of conceptual priming in both related conditions, a proposal incorporated in both swinging lexical network and post-lexical accounts (e.g., Abdel Rahman & Melinger, 2009; Mahon et al., 2007).

**Conclusions.** The experiment reported here indicates that thematic and categorical relations between target and distractor produce different effects in PWI, involving both common and distinct neural processing components. In particular, we show for the first time that thematic relations facilitate naming responses compared to unrelated items, and involve differential engagement of the left middle-MTG and angular gyrus when contrasted with categorical relations that slow target naming. Combined with recent lesion evidence implicating the angular gyrus in processing of thematic relations (Schwartz et al., 2011), the present results provide novel information concerning the role of the IPL in spoken word production (e.g., Indefrey,
2011).
References


(TEM) volume coil for high-field NMR. *Magnetic Resonance in Medicine, 47*, 990-1000.


Footnotes

1We are grateful to two anonymous reviewers for bringing the issue of a potential repetition suppression effect to our attention.

2Mahon et al. (2007) use the term “semantic priming” while Costa et al. (2005) explicitly invoke a pre-lexical, conceptual locus for facilitation effects.

3As noted earlier, this account involving an articulatory buffer and verbal self-monitor also predicts differential activity in premotor cortex and bilateral STG for this contrast, neither of which were observed (e.g., de Zubicaray et al., 2012).
Appendix

Materials used in the experiment

<table>
<thead>
<tr>
<th>Picture</th>
<th>Thematically related</th>
<th>Categorically related</th>
<th>Unrelated related</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACORN</td>
<td>squirrel</td>
<td>carrot</td>
<td>shampoo</td>
</tr>
<tr>
<td>BABY</td>
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<td>priest</td>
<td>plow</td>
</tr>
<tr>
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<td>perch</td>
<td>horse</td>
<td>priest</td>
</tr>
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<td>river</td>
<td>tomb</td>
<td>squirrel</td>
</tr>
<tr>
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<td>bat</td>
<td>sea</td>
<td>soup</td>
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<td>plane</td>
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<td>zoo</td>
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<td>soup</td>
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<td>chain</td>
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<td>movie</td>
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Table 1. Mean naming latencies (RTs) in milliseconds and errors for distractor-target conditions

<table>
<thead>
<tr>
<th>Distractor Condition</th>
<th>Categorically related</th>
<th>Thematically related</th>
<th>Unrelated</th>
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<td><strong>RT</strong></td>
<td>833</td>
<td>787</td>
<td>803</td>
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<tr>
<td></td>
<td>(93)</td>
<td>(89)</td>
<td>(81)</td>
</tr>
<tr>
<td><strong>Errors</strong></td>
<td>.47</td>
<td>.94</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>(.62)</td>
<td>(1.2)</td>
<td>(1.1)</td>
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Standard deviations in parentheses.
Table 2. Cerebral regions showing significant activity for comparisons of distractor-target conditions in the fMRI experiment

<table>
<thead>
<tr>
<th></th>
<th>Peak MNI (x y z)</th>
<th>Z score</th>
<th>Cluster Size (Voxels)</th>
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<tbody>
<tr>
<td><strong>Thematically related &lt; Unrelated</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left superior occipital gyrus and cuneus&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-21 -93 24</td>
<td>4.05</td>
<td>61</td>
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<tr>
<td>Left middle temporal cortex (MTG)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-57 -12 -15</td>
<td>3.46</td>
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<tr>
<td><strong>Categorically related &lt; Unrelated</strong></td>
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<tr>
<td>Right parietal lobule and cuneus&lt;sup&gt;a&lt;/sup&gt;</td>
<td>27 -78 48</td>
<td>4.48</td>
<td>148</td>
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<td>4.14</td>
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**Thematically > Categorically related**

<table>
<thead>
<tr>
<th>Region</th>
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<th>Y</th>
<th>Z</th>
<th>Value</th>
<th>Cluster FWE</th>
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<tr>
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<tr>
<td>Left MTG (b)</td>
<td>-57</td>
<td>-9</td>
<td>-18</td>
<td>3.35</td>
<td>9</td>
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</table>

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Height threshold \(p < .001\) and \(p < .05\) cluster FWE

\(a\)Whole brain corrected. \(b\)Small volume corrected.

MTG – middle temporal gyrus; SMA – supplementary motor area.
Figure 1. Cerebral regions of interest (ROIs) derived from maximum probability maps (MPMs; Eickhoff et al. 2005; Hammers et al. 2003) used for small volume corrections (SVC) rendered on an inflated left hemisphere surface of an individual brain. Anterior temporal lobe (ATL; green), middle temporal cortex (yellow), posterior temporal cortex (red), superior temporal gyrus (STG; orange), inferior parietal cortex (blue), premotor cortex (purple).
Figure 2. Cerebral regions showing significantly reduced activity for thematically related compared to unrelated distractors in the ROI and whole brain analyses superimposed on the inflated surface rendering of an individual brain (height thresholded at \( p < .001 \) and cluster thresholded at 16 voxels for viewing purposes). (a) left hemisphere lateral view, (b) left hemisphere medial view, (c) right hemisphere lateral view, (d) right hemisphere medial view.
Figure 3. Cerebral regions showing significantly reduced activity for categorically related compared to unrelated distractors in the ROI and whole brain analyses superimposed on the inflated surface rendering of an individual brain (height thresholded at $p < .001$ and cluster thresholded at 20 voxels for viewing purposes). (a) left hemisphere lateral view, (b) left hemisphere medial view, (c) right hemisphere lateral view, (d) right hemisphere medial view.
Figure 4. Cerebral regions showing significantly increased activity for thematically related compared to categorically related distractors in the ROI and whole brain analyses superimposed on the inflated surface rendering of an individual brain (height thresholded at $p < .001$ and cluster thresholded at 9 voxels for viewing purposes). (a) left hemisphere lateral view, (b) right hemisphere medial view.