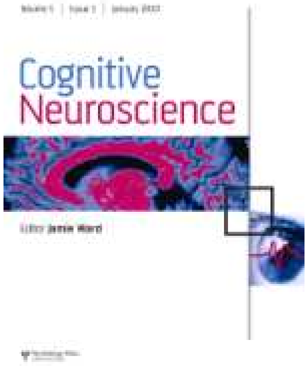

The Neural Basis of Conceptual Combination

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Running head: NEURAL BASIS OF CONCEPTUAL COMBINATION

The neural basis of conceptual combination

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Abstract

Conceptual combination is an essential cognitive process, yet little is known about its neural correlates. In the present study, a categorization task was used to evoke patterns of neural activation for complex concepts (e.g., *young man*) as well as their constituents (e.g., *young*, *man*). A functional region of interest (fROI) within left anterolateral temporal lobe was identified as a possible site of conceptual combination. In this region, the superimposition of activity for constituent concepts reliably predicted the activation pattern for the complex concept built from those constituents.

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The neural basis of conceptual combination

Concepts are mental representations of natural categories, e.g., *lamps*, *lions*, *roses* (Murphy, 2004). Their manipulation underlies cognitive processes as fundamental as categorization and language acquisition (Fodor, 2008; Murphy, 2004). For this reason, neuroscientists have been interested in understanding the neural basis of conceptual competence (Martin & Chao, 2001; Warrington, 1975). One unresolved question is whether conceptual representations are amodal (Fodor, 2008; Patterson, Nestor, & Rogers, 2007) or based in sensory systems (Barsalou, 1999; Goldstone & Barsalou, 1998); they might also be a hybrid of both (Davies, 2004; Dove, 2009). In contrast, there is greater agreement about neural sites, with activation of temporal and lateral frontal cortices often reported to be correlated with conceptual tasks (Davies, Halliday, Xuereb, Kril, & Hodges, 2009; Lambon Ralph, Pobric, & Jefferies, 2009; Martin & Chao, 2001; Noppeney & Price, 2004; Poldrack et al., 1999; Rogers et al., 2006; Warrington, 1975). Experiments on conceptual processing typically involve monolexemic concepts, that is, categories expressed with a single word (e.g., Poldrack et al., 1999, Noppeney & Price, 2004). Determining the neural correlates of such concepts has revealed much about conceptual knowledge. The focus on monolexemic concepts, however, has left some issues comparatively unexplored, notably, **conceptual combination**.

Conceptual combination is the process whereby complex concepts are constructed from simpler constituents (e.g., *young man* from *young* and *man*). Generating such combinations is essential to the open-ended, creative character of human cognition, allowing the production of an unlimited set of ideas from a finite base (Fodor, 2008). One of the simplest forms of combination is illustrated above wherein a modifier is applied to a substantive/head concept. This case has been subject to intense investigation within psychology and several theories have attempted to describe the mechanisms underlying it (Murphy, 2004, chap. 12). One such theory is the Selective Modification Model (SMM) of Smith, Osherson, Rips, and Keane (1988). This model is confined to adjective-noun phrases like *young man* or *red apple.* According to the SMM, the conceptual representation of the substantive is defined in terms of a set of dimensions (color, shape, size, etc). Each dimension assumes a profile of possible features (for color: red, green, yellow, etc.) weighted by typicality. During conceptual combination, the modifying concept adjusts these weights. For example, when *brown* and *apple* are combined into *brown apple,* the weight for the color attribute is enhanced, and the color-feature is adjusted (from red to brown). This process explains several phenomena regarding the application of concepts to exemplars (see Smith, Osherson, Rips, & Keane, 1988).

The SMM works well for conceptual combinations with modifiers that univocally affect specific attributes (*brown* nearly always applies to the color attribute). The SMM encounters difficulties, however, when the impact of the modifier depends on the substantive, as in relative adjectives like “sharp” (sharp razors are sharper than sharp knives). This impact is especially clear when semantic features emerge from the combination without being present in either constituent. To illustrate, the complex concept *winter underwear* is associated with longer length and increased warmth, yet these features are coded in the meaning of neither *winter* nor *underwear*. Accounts of such “syncategorematic” effects have been proposed by

Gagné & Shoben (1997), Hampton (1988), Murphy (1988), and Wisniewski (1996) among others.

Interest in emergent semantic features, however, should not be allowed to obscure the role of categorical meaning in conceptual combination. For, some aspects of the sense of complex terms result from predictable interactions of the senses of their constituents.

Consistent with such a combinatorial process, Swinney and colleagues (2007) have used lexical priming to document that the categorical features of constituents are psychologically available prior to the availability of emergent properties of their combinations. Let it also be noted that properties that seem to be emergent (e.g., the recalcitrance of obtuse politicians, which is coded by neither constituent) may sometimes reflect mere phonological conflation of distinct lexical items; for example, “obtuse” in “obtuse angle” versus “obtuse politician” (for discussion, see Murphy, 1988). Such uses might also be partly metaphorical (Glucksberg, 2001).

In the present study, we leave emergent properties to one side, and focus instead on the simplest case of conceptual combination, using adjectives and nouns that seem to combine categorically. It is assumed that the modifiers *young* and *old* combine in this basic way with the substantives *man* and *woman*. We attempt to identify the neural regions that implement the first steps in the combinatorial process. In these first steps, we expect the meaning of each constituent to be represented in the meaning of the combination. The simplest realization of this idea is *superimposition*, in which the activations proper to the two constituents combine additively in the activations of the complex concept. Thus, regions will be sought that represent the activation associated with a complex concept (e.g., *young man*) as the superimposition (addition) of the representations of the constituent concepts (*young* and *man*).

The neurophysiological correlates of adjective-noun combinations have not been directly examined in previous studies. But the more general phenomenon of "semantic unification" has already been the focus of both ERP and neuroimaging experiments. Semantic unification refers to the integration of meaning across multilexemic stretches of discourse (Hagoort, Baggio, & Willems, 2009). It has been observed that the response of the left anterior temporal lobe is correlated with the semantic complexity of the phrase to be unified (Rogalsky & Hickok, 2009; Vandenberghe, Nobre, & Price, 2002). However, the left temporal lobe is not the only region implicated in semantic unification, as the lateral frontal cortex has also been shown to play an important role (for a review see, Hagoort, Baggio, & Willems, 2009). It seems plausible that the neural sites revealed in semantic unification tasks are also implicated in combining adjectives and nouns.

To identify brain regions involved in the first steps of adjective-noun conceptual combination, we performed two experiments. In both, simple concepts were the single lexical units *young*, *old, woman*, *man*, and complex concepts were the combinations *young woman, old woman, young man, old man*. In the first experiment, the "unitization" of conceptual combinations was evaluated. Unitization denotes the chunking of complex stimuli into more easily processed pieces of information (Drewnowski & Healy, 1977). In the present context, the unitization of complex concepts is operationalized as the absence of a significant difference between the reaction times for categorizing simple versus complex concepts. The absence of unitization would make it difficult to determine whether a brain region that showed additive conceptual combination was displaying the impact of phonological looping (e.g., *young* followed by *man*) rather than superimposition of constituent concepts. In a second experiment, participants completed a functional magnetic resonance imaging (fMRI) task. Functional regions of interest (fROIs) were obtained from a contrast sensitive to both perceptual and conceptual components of the experiment. Within each fROI it was then determined whether the superimposition of the voxel-wise neural representations of simple constituent concepts approximated the neural representations of complex concepts. We expected such superimposition to be observable in brain regions consistent with previous research on semantic unification (namely, the left anterior temporal lobes or the left lateral frontal cortex).

Method

Participants

Twelve Princeton University undergraduate students (8 female) participated in a preliminary behavioral study. A different group of ten graduate and undergraduates (all female) participated in the same behavioral paradigm followed by an fMRI study.

Stimuli

The experiment was based on four simple and four complex concepts, namely, *young*, *old*, *man*, *woman* and *young man*, *young woman*, *old man*, *old woman*. *FaceGen Modeller 3.1* (Singular Inversions, 2006; Todorov, Baron, & Oosterhof, 2008) was used to generate 112 faces, 28 per complex concept (see Figure 1). Seventy-two of the faces were used to create six sequences of 12 (no repeated faces). In a given sequence, each of the four complex concepts was satisfied by three faces. These six sequences will be termed "targets." Twenty-four different faces from the original set of 112 were set-aside as "fillers." The remaining 16 faces were called "hash mark faces;" each sported a small, randomly placed hash mark (#). Twelve randomly selected target faces were also chosen to sport an arbitrarily placed hash mark, and were then added to the hash mark faces. These faces, without hash marks, also remained within their respective target sequences.

Participants confronted these stimuli in a behavioral task and an fMRI task. The purpose of the behavioral task was to ensure that complex concepts were unitized (each processed as a single concept rather than a serial process of each constituent concept). We describe it first, followed by the fMRI task. (Figure 1 about here).

Behavioral task

The 72 faces composing the target sequences and the 24 filler faces were employed. On a given trial, one of the eight concepts was written on screen followed by the 96 faces in random order in a self-paced serial presentation. For each face, the subject indicated "yes" or "no" as fast as possible according to whether the face satisfied the search category (inputs were collected via keyboard). Our measure of interest was the response time (RT) to categorize each face. Each of the eight concepts served as search category in one trial (768 faces classified in all); the order of the eight concepts was individually randomized.

fMRI task

The fMRI task was divided into four types of trial. A given trial consisted of a randomized sequence of faces, with each face presented for 850 ms followed by a 400 ms fixation cross. Preceding each trial, participants were shown a written display (lasting five seconds) of one of the eight concepts or the words "hash mark". If shown a concept, subjects were to decide whether each face belonged to the given concept category. If shown ‘hash mark’, participants were to decide whether each face contained a hash mark (the presence of a hash mark on a given face was determined randomly). Question marks occasionally appeared within the sequence of faces. When a question mark appeared, subjects were to respond on the basis of the face preceding it, e.g., affirming that a face was a young woman or that it held a hash mark, depending on the written display and the character of the face preceding the question mark. We now describe the four types of trial.

“Target” trials consisted of a target sequence lasting 15 seconds (12 faces). A question mark never appeared during target trials.

“Catch” trials consisted of a sequence of between one and 11 faces, followed by a three second question mark, then a fixation cross bringing the trial to 15 seconds. The presented faces consisted of filler and up to four randomly selected target faces. The purpose of the catch trials was to ensure vigilance in the target trials, obliging subjects to maintain the concept in mind throughout. Subjects had no way of distinguishing target from catch trials prior to appearance of the question mark.

“Hash mark” trials consisted of a presentation of 12 faces drawn from the filler and hash mark faces. A question mark never appeared during hash mark trials.

“Hash mark catch” trials consisted of a presentation of one to eleven faces drawn from the filler and hash mark faces, followed by a three second question mark, then a fixation cross bringing the trial to 15 seconds.

Faces from the target sequences were included in each of the four trial types to keep subject unaware of the differences between each type. We note that the same target sequences were presented for each of the eight concepts during target trials. Thus, in target trials, different concepts were maintained in mind while viewing the same sets of faces. Therefore any difference in neural activation between concepts was the result of their mental representation rather than the stimuli themselves. Because faces were presented in random order, no participant noticed that the same target face appeared across different fMRI runs.

fMRI procedure

A scanning session consisted of an anatomical image scan followed by eight data acquisition runs. Each run was composed of six target, two catch, five hash mark, and two hash mark catch trials. Each of the eight concepts (four simple, four complex) was the search category in exactly one of the eight concept trials (six target or two catch trials). These eight trials were interleaved with the seven hash mark and hash mark catch trials. The order of concept-targets within a run was pseudo-randomized so that every concept preceded or followed every other concept. Over all eight runs, each concept was searched for in a target trial six times and in a catch trial two times.

Image Acquisition

Blood oxygen level-dependent (BOLD) activation was used as a measure of neural activation. Echo planar images (EPI) were acquired (TR= 2 s, TE=30ms, FA= 80º, matrix size 64x64) using a Siemens 3.0 Tesla Allegra Scanner (Siemens, Erlangen, Germany) with a ‘bird-cage’ head coil. Whole brain coverage was achieved via 33 interleaved 3 mm axial slices (1 mm inter-slice gap). A high-resolution anatomical image (T1-MPRAGE, TR= 2.5 s, TE= 4.3ms, FA= 8º, matrix size= 256x256) was acquired for functional data registration and cross-subject spatial normalization.

Image Analysis

All fMRI data were treated with *Analysis of Functional Neuro-Images* software (AFNI; Cox, 1996). For each participant, motion was corrected using a six-parameter 3D motion correction algorithm following slice scan-time correction. All data were spatially smoothed with a 6 mm full width at half maximum Gaussian kernel. Data were then low-pass filtered with a frequency cut-off of 0.1 Hz. Finally, signal was normalized to percent difference from the mean.

For each participant, voxel-wise multiple regression was used to generate parameter estimates. Nine regressors of interest (eight concepts and hash marks) were convolved with a canonical hemodynamic response function and entered into a general linear model. Motion estimates and all catch trials were included as regressors of no interest. The subsequent parameter maps for each concept and hashmark were projected into Talairach space (Talairach & Tournoux, 1988) and averaged across all participants.

Results

Behavioral Results

Unitization implies that RTs associated with complex concepts are no longer than RTs for simple concepts. Across all subjects, 13 responses lasting longer than 5,000 ms were counted as outliers and removed from the full dataset. Consistent with unitization, average RT for simple concept categorizations (*young, old, man, woman)* was 643 ms (SD = 145) whereas it was 594 ms (SD = 119) for complex concept categorizations (*young man, young woman, old man, old woman*). This RT difference is significant by t-test ($t(11) = 2.23$, $p < 0.05$, $d = 0.64$) but not sign rank test ($Z = 1.03$, $p > 0.05$). Error rates were negligible for both simple and complex concept categorization (2.26% and 1.26% respectively).

Prior to taking part in the fMRI study, participants completed the behavioral task. This version of the task contained a single random order of trials, and we compared the last trial of each type of concept. Again, evidence of unitization emerged: the RT for simple concepts was 617 ms (*SD* = 282) compared to 546 ms (*SD* = 248) for complex concepts, significantly different via both *t*-test ($t(8) = 3.62$, $p < 0.05$, $d = 1.25$) and sign rank test ($Z = 2.42$, $p < 0.05$). As before, error rates were negligible for both simple and complex concept categorization (2.1% and 3.8% respectively). (One subject's data were not included due to data loss).

fMRI Results

Theories concerning the neurophysiological basis of conceptual knowledge have implicated both perceptual (Barsalou, 1999) and higher order cognitive systems (Patterson, Nestor, & Rogers, 2007). Consequently, we chose to define functional regions of interest (fROIs) using a contrast that would be sensitive both to perceptual and cognitive representations of faces: a group-level contrast (*t*-test) for hash mark versus target trials was used to isolate the fROIs that were queried in subsequent analyses. Significant clusters were defined as contiguous voxels with $p < 0.01$, $t(9) > 3.25$, and a minimum volume of 2000 mm^3. One cluster spanning aspects of right temporal and parietal lobe via the lateral sulcus was split along the sulcus into two anatomically meaningful clusters. The resulting fROIs are listed in Table 1. (Table 1 about here).

In each fROI, the average neural activations for simple and complex concepts were normalized from 0 to 1. Simple concepts were then added together to form additive conceptual combinations (CCs) to estimate neural representations for complex concepts in a given fROI. For example, *young* was added to *man* (*young* + *man*) to form the CC for *young man*. All CCs were then normalized from 0 to 1. We relied on Williams's test of dependent correlations (Steiger, 1980), to determine whether a spurious CC (*young* + *woman*) was better correlated than an appropriate CC (*young* + *man*) with a given complex concept (*young man*). Specifically, each complex concept (eg. *young man*) was correlated with the four CCs. One of the four CCs was appropriate (*young* + *man*). The remaining three CCs were spurious. One of the spurious CCs matched the target concept just in head noun (*old* + *man*), another matched just in modifier (*young* + *woman*), and the third matched neither (*old* + *woman*). The three spurious correlations were compared to the appropriate CC correlation via three Williams's tests. This was done for all four of the complex concepts. In a given fROI, there were thus 12 opportunities for appropriate CCs to be better correlated than spurious CCs with their complex concepts.

We tallied the number of correlations that were significantly stronger for appropriate versus spurious CCs. The last column of Table 1 reports the performance of each fROI. An area of left anterolateral temporal lobe (lALT) emerged as the fROI with highest performance (see Table 1 & Panel A of Figure 2). Indeed, nine of the possible 12 comparisons for lALT were significantly in favor of the appropriate CCs; moreover, the correlation between appropriate CCs and their complex concepts was higher than for spurious CCs in *all* 12 cases (Table 2). The addition of activation for simple concepts to form the CC for the associated complex concept is illustrated in Panels B-E of Figure 2. (Table 2 and Figure 2 about here).

We also performed the following permutation test on lALT. Each of the four simple concepts figured in six trials (see Methods). We randomly permuted the labels of these 24 trials and tallied the number of correlations in which a given complex concept was correlated most strongly with its appropriate CC versus spurious CCs. As before, there are 12 such comparisons. Only seven of 10,000 permutations produced tallies of 12, suggesting that the tally of 12 for the unpermuted data from lALT is not due to chance.

General Discussion

The lALT fROI allows activations associated with complex concepts (e.g., *young man*) to be predicted from the sum of the activations associated with their simple constituents (e.g., *young* + *man*). No other fROI performed nearly as well. The localization of conceptual additivity to lALT is consistent with previous reports of the role of the temporal lobe in conceptual knowledge (Mahon & Caramazza, 2009), specifically, regions overlapping lALT (Leveroni et al., 2000; Zahn et al., 2007). The same regions have also been implicated in processing complex semantics, for which conceptual combination is obviously essential (Rogalsky & Hickok, 2009; Vandenberghe, Nobre, & Price, 2002).

lALT is largely confined to the anterior temporal lobe. The anterior temporal lobe appears to underlie semantic and conceptual processing in both healthy (Pobric, Jeffries, & Lambon Ralph, 2007) and patient populations (Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004). The region is amodal in the sense that it responds equally to semantic information presented via speech, written words, or pictures (Visser, Jefferies, & Lambon Ralph, 2009). Such amodality is likely the result of extensive reciprocal connections from prefrontal cortex, visual and auditory association cortices, and the limbic system (Markowitsch, Emmans, Irle, Streicher, & Preilowski, 2004; Patterson, Nestor, & Rogers, 2007). This cortical interconnectivity and the region's amodal response to conceptual information has led some researchers to propose that the anterior portion of the temporal lobe acts as a semantic hub: a region responsible for the cross-modal binding and high-level processing of conceptual knowledge (Patterson, Nestor, & Rogers, 2007).

The meaning of many adjective-noun combinations may derive from the substitution of semantic features from the adjective into corresponding slots in the noun (e.g., *young* into the unoccupied slot for age within *man*). Such a process is envisioned in Smith et al. (1986) and was recently discussed by Connolly et al. (2007). It is plausible that the transfer of features from adjective to noun requires simultaneous activation of both concepts, yielding the kind of superimposition of activation seen here in lALT. This superimposition might be an early stage of conceptual combination, with later stages recruiting brain regions that engage in deeper analysis of the combination. Such analysis might allow recognition that *young mountains* are older than *young men*, that *wooden spoons* tend to be thicker than the metal variety, and likewise for other emergent properties of complex concepts (Hampton, 1997).

The previous literature on semantic unification is consistent with the hypothesis that lALT prepares complex concepts for subsequent processing in the left lateral frontal cortex. Indeed, Hagoort and colleagues (2009) suggest that the left lateral frontal cortex is responsible for constructing semantic representations of complex ideas not already stored in long-term memory. Such a function is a creative one, and could underlie the production of emergent features thereby illuminating the syncategormatic aspect of conceptual meaning. Note that if the lateral frontal cortex processed late-stage representations of complex concepts, it would not be expected to show the type of additive combination seen in lALT. In fact, only two and five of the 12 correlation-comparisons that reveal superimposition in lALT are significant within left Brodmann areas 44 and 45.

Was the additivity a result of subvocalization (phonological looping) of a complex concept's constituents? Some studies suggest that secondary auditory cortex, overlapping with lALT, may be involved in subvocal word imagery (Kraemer, Macrae, Green, & Kelley, 2005). Most research examining the neural correlates of verbal working memory, however, implicates inferior lateral frontal lobe and parietal lobe regions (Awh et al., 1996; Shivde & Thompson-Schill, 2004), not lALT. Moreover, the unitization results discussed above suggest that complex concepts were processed as fast as their constituents whereas phonological looping would predict otherwise. We observe furthermore that a region including left Heschl's gyrus (containing primary and part of secondary auditory cortex) failed to produce correlations of the kind found in lALT, with only four of 12 significant. As previously mentioned, left Brodmann areas 44 and 45 also performed poorly. The aforementioned regions might be expected to reflect phonological looping if such looping occurred; the absence of conceptual superimposition in these regions thus suggests that looping was not present.

Overall, the results reported here, along with the previous literature on the anterior temporal lobe, suggest that conceptual combination begins to unfold in lALT. We propose that the superimposition of constituent concepts in lALT prepares complex concepts for later stages of combination within the left lateral frontal cortex. The efficacy of such a model and its extension to other complex types of conceptual combination are critical topics for further inquiry.

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Figure Captions

Figure 1. Examples of the four categories of faces used as stimuli and one example of a face containing a hash mark. From left to right: young man, old man, old woman, young woman, and young man with a hash mark.

Figure 2. Left anterolateral temporal lobe fROI (lALT) and an example of addition of a CC (*old* + *woman*) via surface renderings of average neural response patterns to concepts. (A) lALT. (B) *Old.* (C) *Woman*. (D) The calculation of the complex concept *old woman* from a normalized superimposition of *old* & *woman*. (E) The actual neural representation of *old woman.*

Table 1

Largest Voxel Clusters From the Contrast of Hash Marks vs. Target Trials

Region	Center of Mass (x, y, z)	Size ($3mm^3$ voxels)	Peak *t*-value	Dependent correlation *t*-test performance
R. Precuneus	33, -66, 34	1,791	9.54	6/12
L. Precuneus	-38, -64, 31	1,518	9.66	5/12
R. Precentral Gyrus*	61, -20, 23	211	4.04	7/12
L. Precentral Gyrus	-55, -18, 37	182	6.44	7/12
R. Fusiform Gyrus	28, -50, -10	173	9.55	5/12
L. Fusiform Gyrus	-27, -41, -11	170	6.14	1/12
R. Temporal Pole	53, 16, -28	119	7.25	4/12
R. Medial Frontal Gyrus	7, 56, 37	110	7.10	3/12
R. Superior Temporal Gyrus*	63, -30, 6	108	3.91	4/12
L. Medial Frontal Gyrus	-8, 58, 5	96	6.22	3/12
L. Superior Temporal Gyrus (lALT)	**-62, -5, 2**	**87**	**8.53**	**9/12**

Note. Region refers to the anatomical location of the center of mass. Peak t-value is the voxel with greatest activation within the cluster.

* fROI split along lateral sulcus.

Table 2

Correlations in lALT of Appropriate and Spurious CCs With Each Complex Concept

Complex Concept	Appropriate CC	Head Match	Modifier Match	No Match
Young Man	0.657	0.247	0.639	0.138
Young Woman	0.660	0.455	0.639	0.587
Old Man	0.666	0.461	0.455	0.373
Old Woman	0.605	0.370	0.444	0.061
Mean	**0.647**	**0.383**	**0.544**	**0.290**

Note. *Complex Concept* refers to the target complex concept (eg. *young man*). *Appropriate CC* is the calculated CC that correctly corresponds to the *Complex Concept* (*young* + *man* for *young man*). *Head Match* is the CC that only contains the correct head concept constituent of the *Complex Concept* (*old* + *man* for *young man*). *Modifier Match* is the CC that only contains the correct modifier concept constituent of the *Complex Concept* (*young* + *woman* for *young man*). *No Match* is the CC that contains no constituents that match with the *Complex Concept* (*old* + *woman* for *young man*).

Figure 1. Examples of the four categories of faces used as stimuli and one example of a face containing a hash mark. From left to right: young man, old man, old woman, young woman, and young man with a hash mark.
74x22mm (600 x 600 DPI)

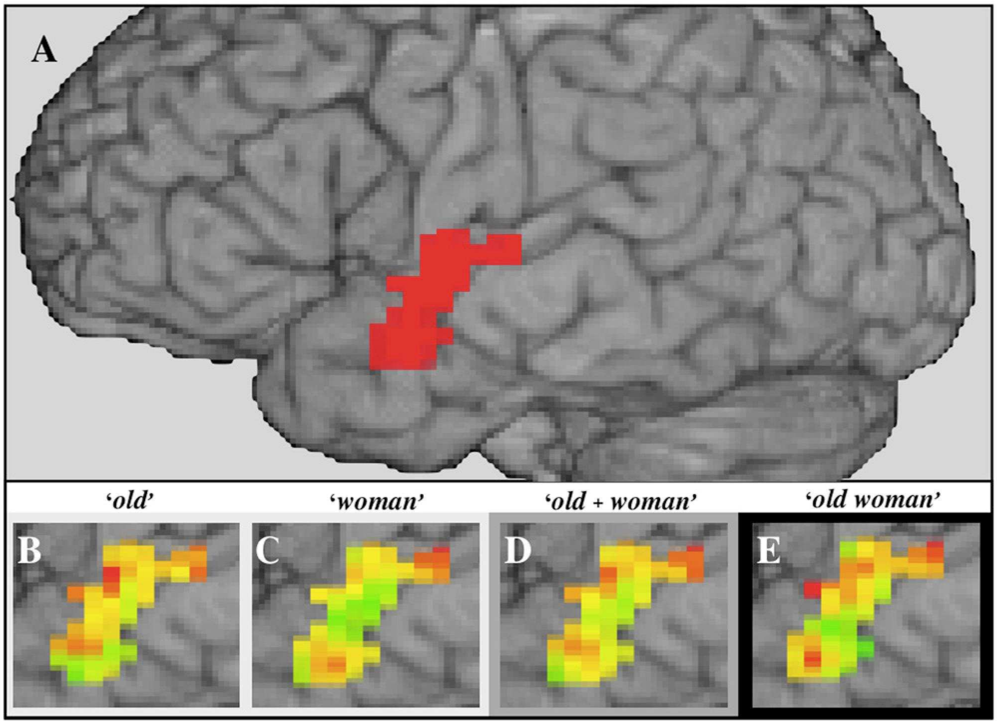

Figure 2. Left anterolateral temporal lobe fROI (lALT) and an example of addition of a CC (old + woman) via surface renderings of average neural response patterns to concepts. (A) lALT. (B) Old. (C) Woman. (D) The calculation of the complex concept old woman from a normalized superimposition of old & woman. (E) The actual neural representation of old woman.
84x61mm (600 x 600 DPI)