The Neural Organization of Semantic Knowledge Reflects Sensory–Motor Attributes

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Introduction

Many neuroimaging studies have addressed the issue of how semantic memory is organized in the brain and how damage to this system gives rise to category-related deficits. One leading theory is that concrete object knowledge is partly “embodied” in the modality-specific perceptual and kinesthetic systems through which objects are experienced. Living things have salient color and visual form attributes, thus their representation may depend heavily on color and form processing systems, whereas tool knowledge relies predominantly on kinesthetic and visual motion representations. Specific tests of this theory have yielded inconsistent and conflicting results. We investigated this issue using event-related fMRI during a semantic decision task involving a very large set of concrete and abstract nouns.

Participants

- Participants in the fMRI study were 25 healthy adults (8 women), aged 18–48 (mean 27) years, with an average of 16.7 years education.
- Other inclusion criteria: - right-handed on the Edinburgh Inventory - English as a first language - normal or corrected-to-normal vision
- Participants performed the following semantic decision task on each item: Is it experienced with the senses?
- Total of 1200 trials presented:
  - All 900 words from the rating study
  - 300 matched pseudowords
  - Each stimulus displayed for 1 sec, followed by a fixation cross
  - Jittered ISI, randomized item sequence
- Right hand 2-choice button response

FMRI Task

- Stimuli
  - Semantic attribute ratings (available at [www.neuro.mcs.wisc.edu](http://www.neuro.mcs.wisc.edu)) were collected from 342 undergraduates who each rated half of a set of 900 nouns on one of 4 attribute domains (Sound, Motion, Manipulation, Color), yielding over 100,000 ratings and approximately 30 ratings per domain per word.
  - Each word was rated from 0 to 6 according to how relevant the target domain was for defining the word (e.g., shudder rates high on Sound but low on other domains; blood rates high on Color but low on others).
- Scanning Parameters
  - GE 3.0-Tesla Scanner
  - 10 runs, 196 images/run = 1960 images
  - 21 slices, 3.75x3.75x6.5 mm voxels
  - TR 2000 ms, TE 40 ms, flip angle 90°
- Design & Analysis
  - Fast Event Related Design - ISI randomly varied from 1–13 sec
- Analysis
  - ANI software package - Images smoothed at 6 mm FWHM - Multiple regression using the following predictor variables:
    - Stimulus event
    - Sound rating
    - Motion rating
    - Manipulation rating
    - Color rating
  - Response time
    - Linear trends, second-order trends, and estimated motion parameters included to model noise.
    - Second-level (random-effects) group analyses performed on coefficient maps for each predictor variable.
    - Group maps thresholded using height (p < .005) and extent (cluster size > 600 mm²) criteria, yielding corrected map-wise significance of p < .05.

Imaging Methods

- BOLD signals in many brain regions were modulated by the degree to which domain-specific sensory-motor attributes were associated with the stimuli. These effects were most evident in left inferior temporal and inferior parietal regions.
- In general, brain regions modulated by the attribute ratings lie in association areas near the sensory and motor systems that process the rated attributes. For example, the inferior parietal regions modulated by Sound ratings are immediately posterior to unimodal auditory cortex. S5S and M1C regions modulated by Motion ratings are just dorsal and anterior to the visual motion processing complex MT and overlap with S5S regions implicated in the perception of biological motion. Regions modulated by Manipulation ratings include premotor (SMA, anterior cingulate) and middle frontal areas strongly implicated in motor planning, as well as a left inferior parietal area believed to play a role in integrating visuospatial and somatosensory information. Lesions in many of these latter regions are associated with ideomotor apraxia, a deficit of motor planning. Finally, Color ratings modulated activity in bilateral ventral extrastriate regions, particularly left fusiform and parahippocampal areas just anterior to the human color perception system. Together, these results provide further evidence that knowledge about concrete objects is organized in part according to the sensory and kinesthetic processing systems through which that knowledge is acquired.

Results: Behavior

- Mean RT across all trials = 853 ms
- Nouns correctly rejected on 96.4% of trials
- Item analyses on the words showed that Attribute Ratings were strongly predictive of both the Response (R = 0.831, F(4,895) = 498.8, p < .0001) and the RT (R = −0.697, F(4,895) = 210.8, p < .0001) on the semantic decision task. Color ratings were the most predictive of performance followed by Manipulation, Motion, and Sound, as shown in the following regression equations:
  - Response (1 = yes, 0 = no) = [0.133×Color] + [0.104×Manipulation] + [0.039×Motion] + [0.037×Sound]

Discussion

- Many of the effects attributed to Color ratings may actually reflect processing of other visual attributes that were not rated in this study. Color ratings were strongly correlated with general imageability ratings for the words (R = 0.78, p < .0001) and are likely to be correlated with many kinds of visual attributes, such as shape, texture and the complexity of spatial relationships between object parts. Future studies will include separate measures for these perceptual domains.
- The results lend support to the idea that many category-related deficits can be explained by damage to distributed semantic feature representations organized according to sensory–motor modality. That is, non–living artifact representations, which depend disproportionately on manipulation and sound knowledge, tend to be disproportionately affected by damage in the posterior temporal–parietal region, while animal and plant concepts are disproportionately affected by damage to ventral and anterior temporal regions storing knowledge about color and other visual attributes.