CONCEPT REPRESENTATION REFLECTS MULTIMODAL ABSTRACTION: A FRAMEWORK FOR EMBODIED SEMANTICS

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CONTENTS

Perception → Comprehension

BACKGROUND

Embodied Semantics: language comprehension involves reactivating sensory-motor experiences from our interactions with the world

Sensory-Motor Cortical Areas: play a crucial role in forming and retrieving concepts related to objects and actions

- Note: even <u>abstract concepts</u> are understood through this framework
- Example: “grasping an idea”

Meaning ↔ Physical experiences and perception

BACKGROUND

Neuroimaging evidence: understanding language involves mental simulations of sensory and motor experiences
🧪 Proof: activation in corresponding brain areas during language processing

Multimodal integration: beyond single sensory-motor domains, certain brain areas integrate multiple sensory and motor experiences, reflecting a more complex aspect of conceptual knowledge.

QUESTIONS

- **Big theoretical question**: To what extent do sensory and motor cortical areas contribute to the neural representation of concepts, and how are these representations influenced by our sensory-motor experiences?
- **Experimental question**: How do various sensory-motor attributes (such as color, shape, manipulation, sound, visual motion) influence the semantic processing of words in the brain?

HYPOTHESES

H1 (Experimental Hypothesis): Different sensory-motor attributes of words activate distinct and specific brain regions associated with the processing of those attributes during

H2 (Alternative Hypothesis): The brain represents sensory-motor attributes of words in an amodal (non-sensory-specific) manner → representation is not tied to the specific sensory or motor system

H0 (Null hypothesis): Sensory-motor attributes of words do NOT significantly activate specific brain regions or networks → these attributes are not distinctively represented during word processing

METHODS: OVERVIEW

Stimuli

- 900 words
  - 600 relatively concrete
  - 300 relatively abstract
  - Various semantic categories
  - NOT distributed equally across sensory-motor domains
  - All familiar
- 300 pseudowords (word-like nonwords)
- 760 passive fixation events (act as baseline and provide jittering for the deconvolution analysis)

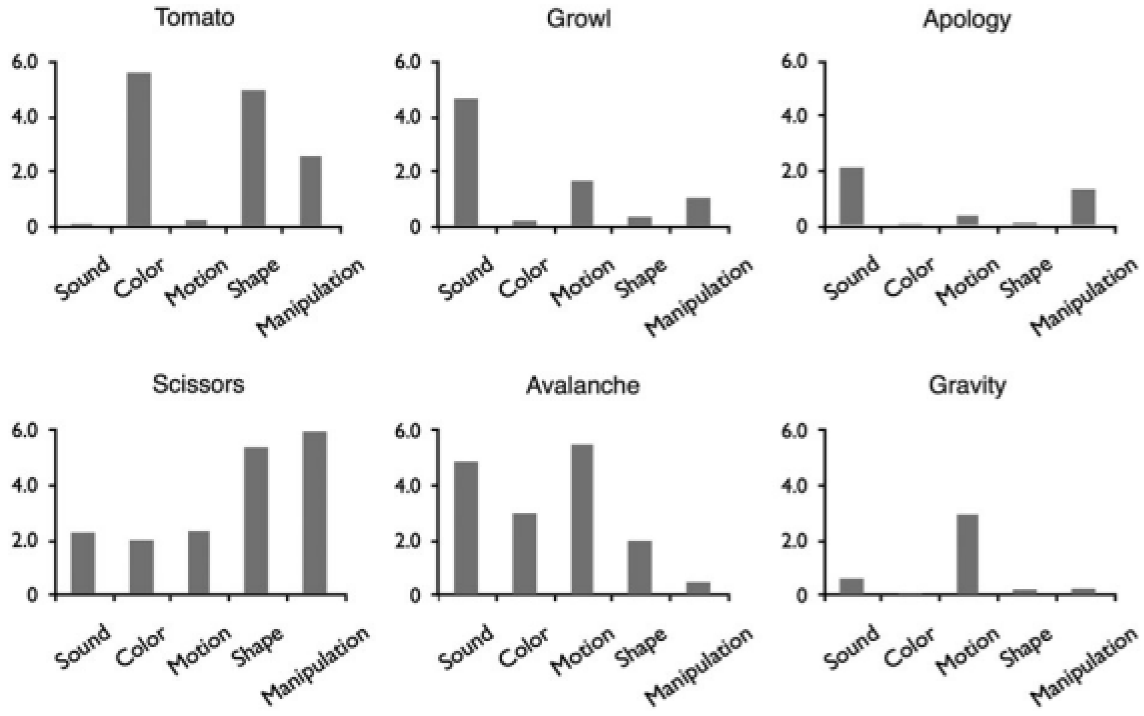
Participants

- 44 healty, native speakers of English
- Mean age: 28,2
- No history of neurological or psychiatric disorders

Attributes

- Color, shape, manipulation, sound, and visual motion (closely tied to sensory-motor experience)
- Rating of the relevance to the meaning of each word obtained from 342 participants on a 7-point scale (from “not at all relevant” to “very relevant”)

METHODS: OVERVIEW



Rating	Mean	SD
Sound	2.00	1.66
Color	1.91	1.65
Manipulation	1.75	1.29
Visual motion	1.74	1.43
Shape	2.47	1.98

⚠ NOT all attributes correspond directly to a modality

- Shape → visual and somatosensory
- Manipulation → motor, visual and somatosensory

☑ All attributes are associated with well-studied cortical regions

METHODS: DETAILS

1. **Presentation of words**: Participants were exposed to the stimuluts during a fMRI scanning in 10 different runs
2. **Participant task**: Participants were required to decide whether the stimulus was:
   - A word (yes)
   - A pseudoword (no)
3. **Recording brain activity**: The brain activity of participants was recorded as they were exposed to these words:
   - 23 scanned on a GE 1.5T Signa MRI scanner
   - 21 scanned on a GE 3-T Excite MRI scanner
4. **Data preprocessing**:
   - The **activity levels** has been:
     - <u>Aligned</u> to the T_1-weighted anatomical volume
     - <u>Transformed</u> into standard space
     - <u>Resampled</u> at 3-mm isotropic voxels
     - <u>Smoothed</u> with a 6-mm FWHM Guassian kernel

METHODS: DETAILS

4. **Data preprocessing**:
    - The **attribute relevance** ratings has been:
        - Transformed to standard z-scores → how many standard deviations a value is above or below the mean
          Goal: provide a way to compare attributes on a common scale
        - Coded separately between abstract and concrete words
          Goal: ensure that only concrete words contribute to the attribute maps
        - Converted to ranks prior to entering the regression model
          Goal: eliminate any differences in the distribution of the ratings by imposing a flat distribution to all of them

5. **Perform different analyses:**
    - **A Full-model analysis**: included all five semantic attributes in a single regression model
      Goal: identify voxels where activity correlated with a given attribute
    - **5 leave-one-out analyses**: performed by excluding 1 of the attributes from the regression model
      Goal: identify activations driven by variance shared between 2 correlated attributes
    - **5 single-attribute analyses**: separate analyses conducted for each attribute alone, combined to create a conjunction map
      Goal: identify regions modulated by all 5 attributes and exclusively 2,3 or 4 attributes
    - **A Principal Component Analysis (PCA)**: on the attribute ratings to explore how their co-occurrence patterns

HYPOTHESES: REVIEW

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PREDICTIONS

If H1 was true: The fMRI data would reveal distinct brain regions correlating with each of the sensory-motor attributes
Example: words with high relevance of ‘color’ should predominantly activate visual areas known for color processing

If H2 was true: The activation patternswould not be confined to specific sensory or motor regions, but we would see a more diffuse activation (potentially in areas associated with higher-order processing)
Example: words with high relevance of ‘color’ should activate the amodal network

If H0 was true: No significant correlation between the sensory-motor attributes of words and activation in any specific brain regions
Example: words with high relevance of ‘color’ would not show specific patterns of activity in the brain

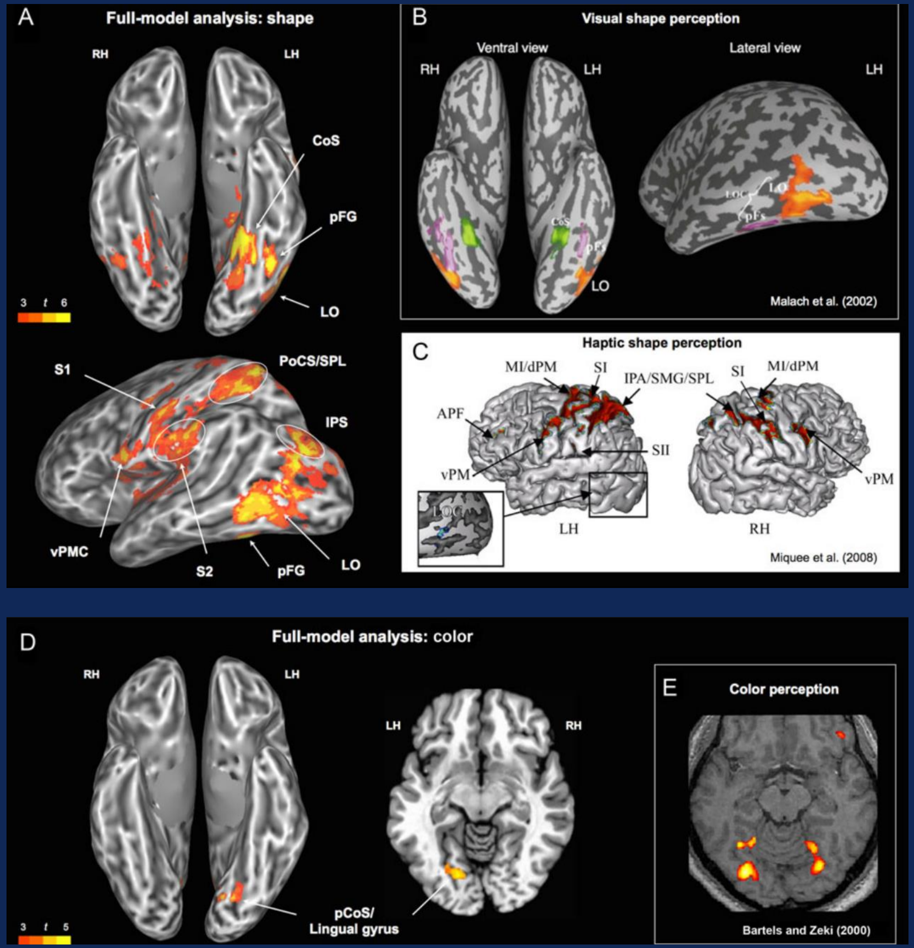
RESULTS

- Participants successfully engaged in the semantic decision task, indicating close attention with mean accuracies
  - 0.84 for words
  - 0.96 for pseudowords
- The fMRI data revealed that cortical areas modulated by semantic attributes included:
  - Uni-modal regions
  - Bi-modal regions
  - Multi-modal regions

  with strong left-lateralization across all attributes

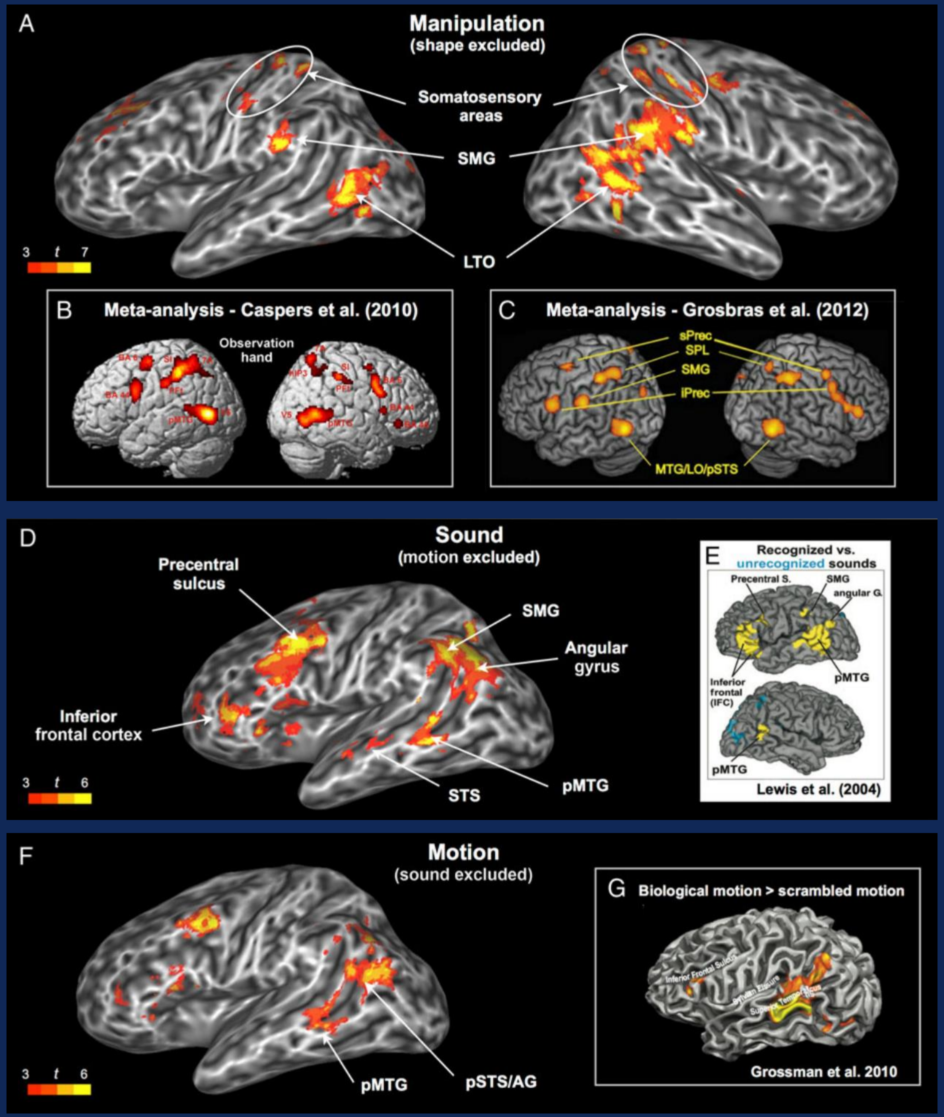
RESULTS

- The **Shape** attribute modulated activity:
  - In the ventral stream areas involved in <u>visual shape analysis</u>: Ventral Occipitotemporal (VOT) and Lateral Occipital Complex (LOC)
  - In the Superior Occipital Gyrus and Posterior Intraparietal Sulcus (IPS), associated with <u>object recognition over faces or scenes</u>
  - In regions processing <u>haptic and visuo-tactile information</u>
  - ☑ Supports **H1**
- The **Color** attribute modulated activity:
  - In the left ventromedial occipital cortex, a part of the ventral visual pathway implicated in <u>color perception</u>
  - ☑ Supports **H1**



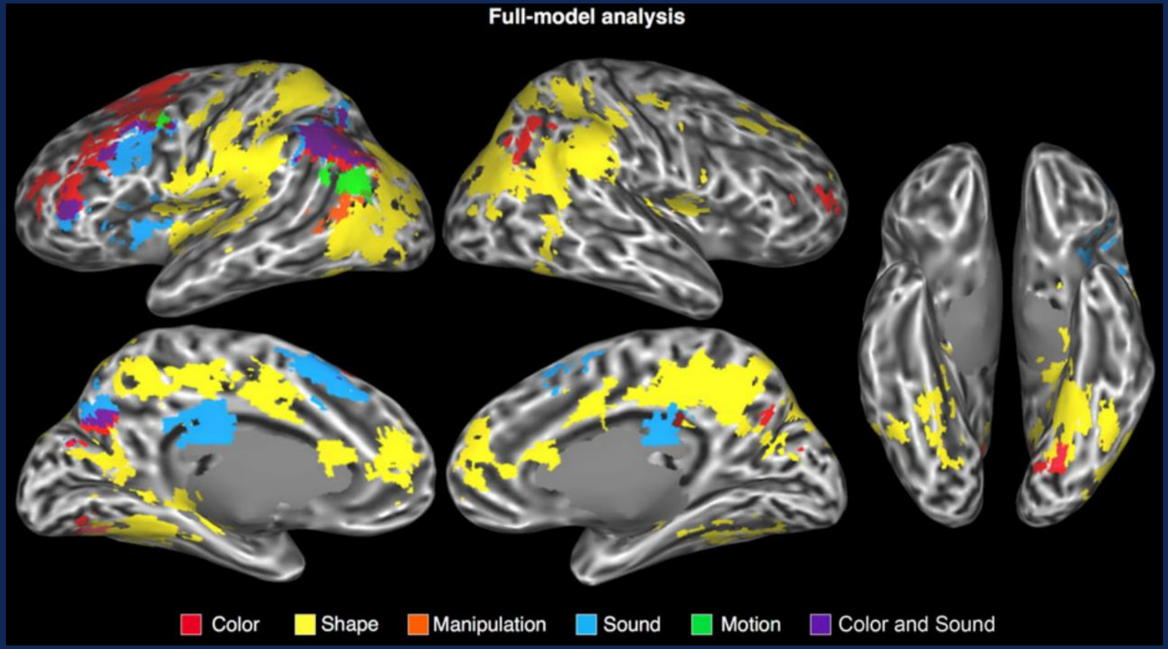
RESULTS

- The **Manipulation** attribute modulated activity:
  - In areas involved in the action representation network, particularly responsive to <u>object-directed hand actions</u>
    - Left posterior middle temporal gyrus (pMTG)
    - Anterior occipital cortex
  - ☑ Supports **H1**
- The **Sound** attribute modulated activity:
  - In the left ventrolateral prefrontal cortex (VLPFC), a region implicated in <u>nonspatial auditory processing</u>
  - ☑ Supports **H1**
- The **Visual motion** attribute modulated activity:
  - NOT in area MT+, typically associated with <u>visual motion</u>
  - In the ventrolateral portion of the left angular gyrus
  - ✗ Support **H2**, suggesting amodal processing



RESULTS

- Results suggests that **H1** is largely supported, as distinct brain regions correlated with sensory-motor attributes were identified, which are involved in processing those specific types of information during word processing.
- The finding for visual motion might hint at a more complex representation that could lend some support to **H2**, but it does not fit the expected pattern for an amodal representation.



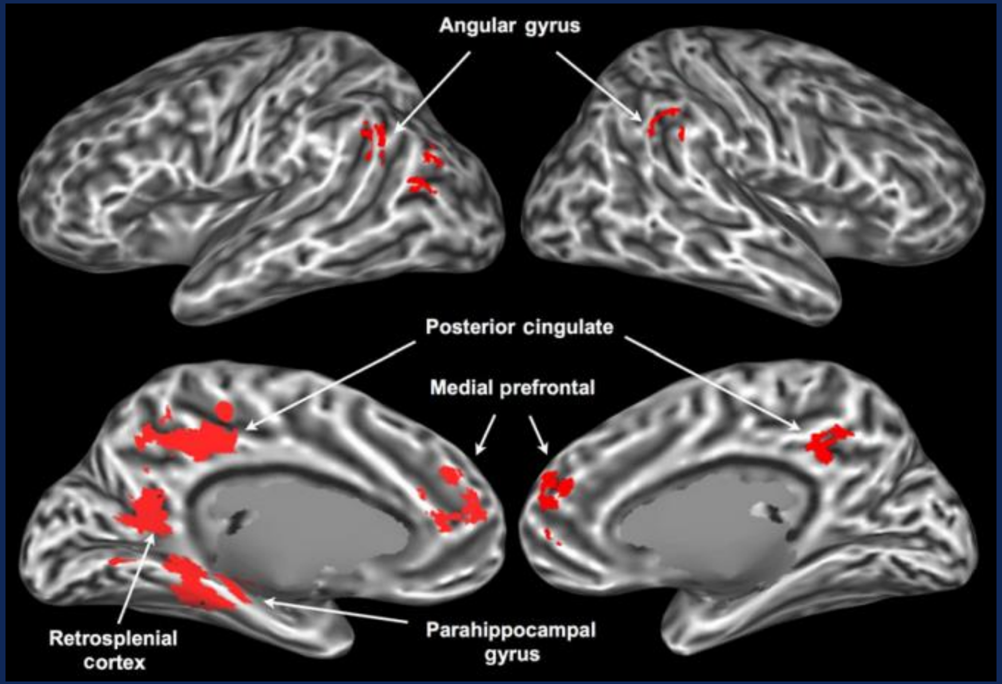
RESULTS

The areas activated by all 5 attributes were:

- **Parahippocampal Gyrus** and **Retrosplenial Cortex**: linked to tasks that involve coordination of multiple representations
  Example: scene recognition and spatial navigation
- **Medial Prefrontal Cortex**, **posterior cingulate/precuneus**, and **angular gyrus**: top-level convergence zones (CZs) for sensory-motor processing and are nodes of the "default-mode" network associated with conceptual processing

all implicated in high-level multimodal integration tasks

⚠ Althouth the **Anterior Temporal Lobes** have been proposed to be a major hub for integrating conceptual information, was not activated by any of the 5 attributes (might be supramodal)



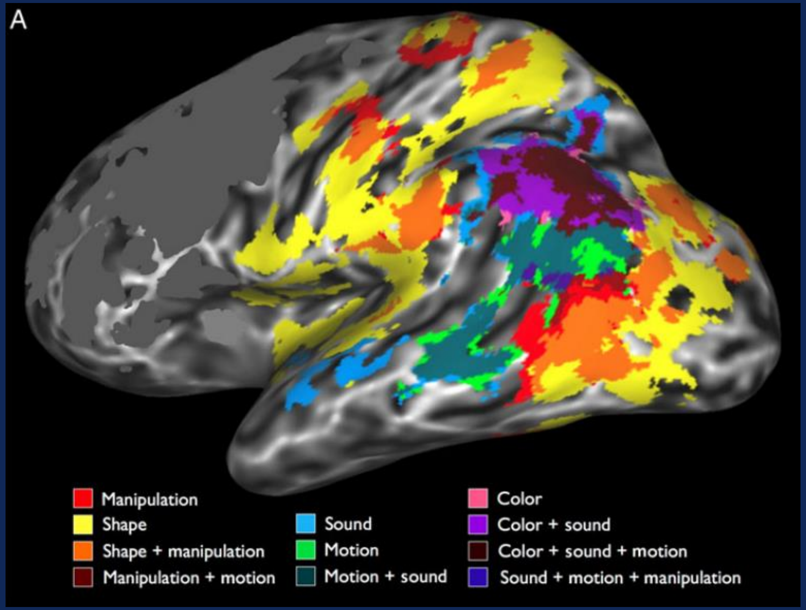
DISCUSSION

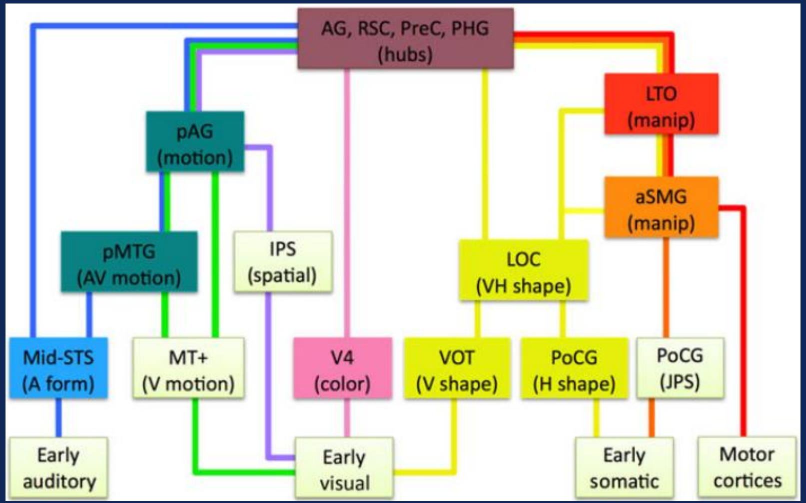
Findings:

1. The cortical regions where activity was modulated by sensory-motor attributes of word meaning consisted mostly of secondary sensory areas and multimodal integration areas
2. The results suggest a **hierarchical system** of sensory and motor pathways with conceptual attributes represented in <u>specific multimodal subnetworks</u>

Theoretical implications:

- Contrary to the **Hub and Spokes Model** (Patterson et al. 2007), which posits a <u>single amodal hub</u> in the temporal pole, the study suggests <u>multiple multimodal integration areas</u> are involved in concept representation.





Note: information flows mainly from low-level modal cortical areas toward multimodal areas and cortical hubs

CONCLUSIONS

- Word meanings are neurally encoded in a manner consistent with embodied semantics
- 4/5 semantic attributes related to distinct sensory-motor experiences correlate with activations in their respective sensory-motor regions
- There is involvement of both early <u>unimodal areas</u> and <u>multimodal areas</u>, depending on the attribute
- The results suggests a complex, hierarchical integration of sensory-motor information within semantic memory

APPENDIX

Both the **Concrete Words Analysis** and the **Rank-Based Analysis** produced very similar results

Indicate robustness in the findings

The **PCA** on the attribute ratings to explore how their co-occurrence patterns map onto the properties of natural ontological categories showed that:

- The 1st component (57% variance) → concrete concepts abstract concepts
- The 2nd component (23% variance) → objects events
- The 3rd component (11% variance) → manipulable entities nonmanipulable entities
- The 4th component (6% variance) → entities associated with motion but no sound entities associated with sound but no motion
- The 5th component (3% variance) → concrete entities with no characteristic shape all the others

The structure reflects correlation patterns between the original attributes as they occur in the world

THANK YOU

Massimo Stefan