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JUDGING SEMANTIC SIMILARITY: AN EVENT-RELATED fMRI STUDY WITH AUDITORY WORD STIMULI

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Abstract—Much of mental life consists in thinking about object concepts that are not currently within the scope of perception. The general system that enables multiple representations to be maintained and compared is referred to as "working memory" [Repovš G, Baddeley A (2006) Neuroscience 139:5–21], and involves regions in medial and lateral parietal and frontal cortex [e.g., Smith EE, Jonides J (1999) Science 283:1657–1661]. It has been assumed that the contents of working memory index information in regions of the brain that are critical for processing and storing object knowledge. To study the processes involved in thinking about common object concepts, we used event related fMRI to study BOLD activity while participants made judgments of conceptual similarity over pairs of sequentially presented auditory words. Through a combination of conventional fMRI analysis approaches and multi-voxel pattern analysis (MVPA), we show that the brain responses associated with the second word in a pair carry information about the conceptual similarity between the two members of the pair. This was the case in frontal and parietal regions involved in the working memory and decision components of the task for both analysis approaches. However, in other regions of the brain, including early visual regions, MVPA permitted classification of semantic distance relationships where conventional averaging approaches failed to show a difference. These findings suggest that diffuse and statistically sub-threshold "scattering" of BOLD activity in some regions may carry substantial information about the contents of mental representations.

Key words: fMRI, conceptual distance, semantic memory, working memory, multi-voxel pattern analysis.

The study of the organization and representation of object knowledge in the human brain has a long tradition in cognitive science, and more recently, has been the focus of numerous functional imaging studies (for review, see Martin, 2007). Many functional imaging studies of semantic memory have focused on understanding how the brain responds to different object concepts (e.g., tools, faces, houses) when they are presented to participants in the form of pictures. However, much of our mental life involves thinking about object concepts that are not, when we think about them, also the objects of perception. Spoken language is one special case of this situation, where auditory information is mapped onto conceptual knowledge about the referent of a word. Thus, auditorily presented words may be used as stimuli for probing the types of knowledge that are retrieved when thinking about objects, in the absence of any visual input.

In the current experiment, we were interested in studying the role played by the similarity between two different concepts being held in working memory in shaping the brain's response to those concepts (see Cantlon et al., 2009, for review and discussion). A set of materials was selected such that every concept (e.g., "Chair") was relatively close (i.e., conceptually similar) to another item in the set ("Stool") and relatively far (i.e., dissimilar) from another concept (e.g., "Stove"). Thus, materials were selected in pairs, such that there was always another concept within the set that was relatively close; the conceptually "far" condition was created by repairing each word with another item from the same broad semantic class. A third level of conceptual distance was the "Identity" condition (every word paired with itself). Conceptual distance (as manipulated between the close and far conditions) was defined at the time of stimulus selection through a combination of intuition and pilot work. However, our measure of conceptual distance is operationalized in terms of participants' actual judgments about the "similarity of the concepts," obtained during fMRI scanning (see below).

Event-related fMRI was used while participants made judgments of conceptual similarity over the pre-selected pairs of auditorily presented words. As described above, the two words presented on each trial could have three levels of conceptual similarity: they could be the same ("Identity" Condition, e.g., Chair–Chair), conceptually similar ("Close" Condition, e.g., Stool–Chair) or relatively dissimilar ("Far" Condition, e.g., Stove–Chair) (see Fig. 1A for a schematic of the trial structure). Across the whole scanning session, and for every participant, the same words appeared as the first and second members of the pairs (i.e., stimulus 1 (S1) and stimulus 2 (S2), respectively), and at all relative distances to the other members of the pairs. In this way, the psycholinguistic properties of the words were "matched" across all conditions of interest (S1, and then within S2, Identity, Close, Far) because the same words appeared in all conditions, just repaired in such a way as to derive the desired manipulation of semantic distance. This design permits a direct test of whether the brain responses associated with processing the second object concept in a pair are modulated as a function of the immediately preceding context (i.e., the first object concept of the pair). The critical manipulation in this regard is

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Abbreviations: FDR, false discovery rate; MVPA, multi-voxel pattern analysis; ROIs, region of interest.

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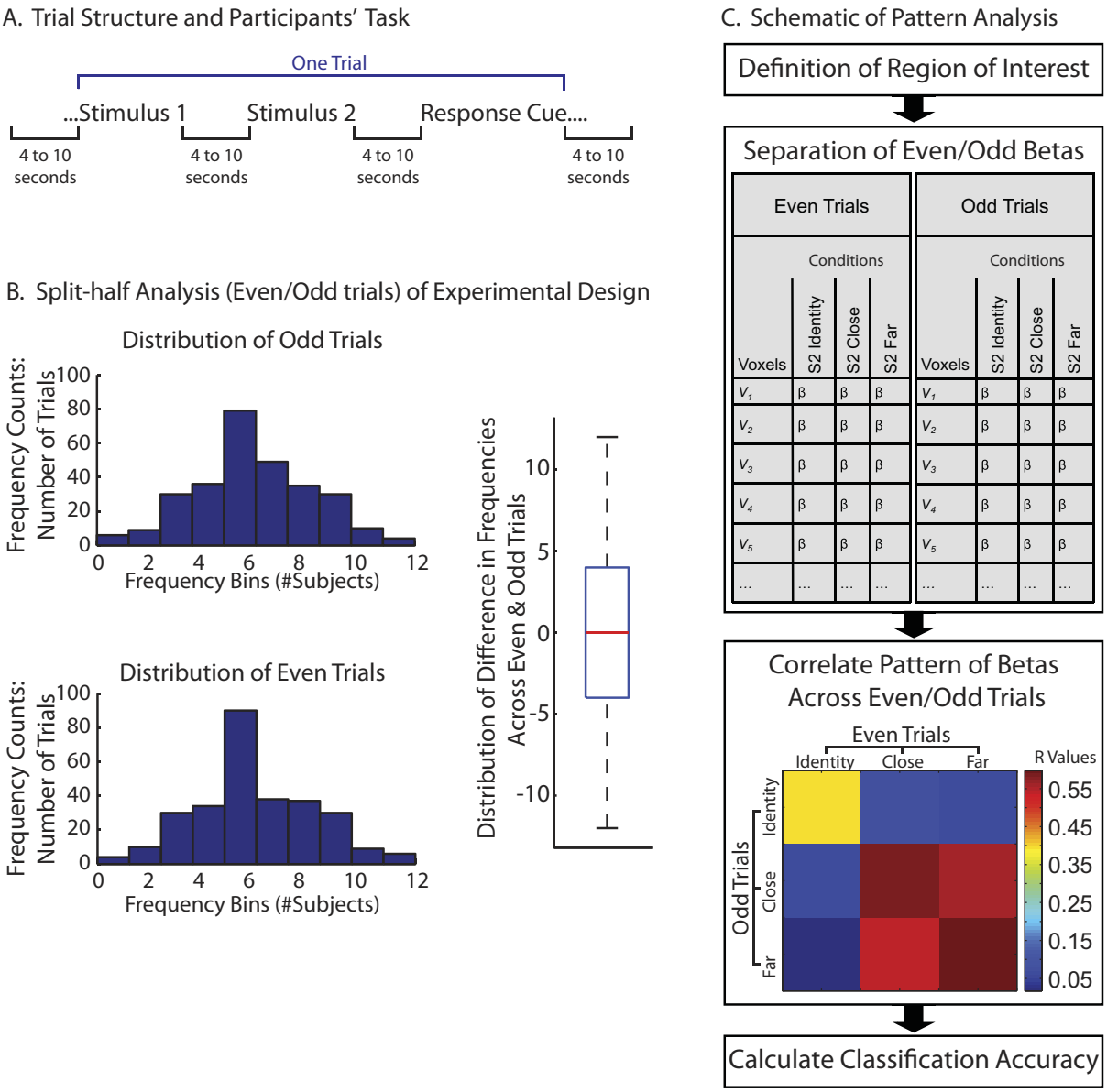

Fig. 1. (A) Structure of trials and analysis. Each stimulus (S1 and S2) consisted of an auditorally spoken word. Participants indicated the conceptual similarity between the pair of words by means of a button response after hearing a response cue (200 ms tone). (B) Functional data were divided into two halves, based on even and odd trials. Because the experimental design was distributed randomly with constraints across trials, the distributional analyses show that the design was balanced across the two halves of the data (even and odd). There were 288 unique trials per subject, and 12 subjects. Thus, the histograms indicate that the distribution of those 288 unique trials was distributed evenly across the even and odd trials, across all subjects. The boxplot substantiates this by representing the difference scores between the two distributions. (C) This panel shows schematically the analysis strategy: Regions of Interest (ROIs) were defined by contrasting S2 against S1, using only even trials for S2. We then tested for differences, using conventional averaging approaches, among Identity, Close, and Far for S2, for odd trials only. We also computed within- and between-condition correlations, always comparing even and odd trials. Classification accuracy was then calculated on the basis of the resulting correlation matrices.

the direct confrontation between the "close" and "far" conditions: one expectation on the basis of previous research (e.g., Rips et al., 1973) is that more fine-grained analysis is required in order to judge the similarity between very close concepts. Associated with such fine-grained processing are increased response times, and it may be predicted, differential BOLD responses, at least in those regions that are sensitive to the degree to which the concepts must be analyzed according to the task.

EXPERIMENTAL PROCEDURES

Participants

Fifteen healthy native Italian speakers, with normal eyesight (corrected with MR compatible goggles where necessary) and normal hearing participated in the experiment. The datasets for three participants were discarded due to excessive head motion. Of the 12 subjects included in the analysis seven were female, 10 were right handed (assessed with Edinburgh Handedness Inventory, Oldfield, 1971), and the group had a mean age of 32.4 years