

Lateralization in Neurosemantics: Are Some Lexical Clusters More Equal Than Others?

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ABSTRACT

We have implemented neurosemantic analysis to identify brain's voxel-wise representations of words in Russian spoken narratives and their asymmetries in the brain. Twelve lexical clusters were found for seven best subjects, with different semantics – from time-and-space concepts to human actions and mental states. Our results support the view of widely distributed nature of semantic representations.

INTRODUCTION

The question of asymmetry of computing processes has an intrinsic value for the build-up of cognitive systems, both natural and artificial. Recently we demonstrated that brain representations of meaningful texts should involve the ideas of situational semantics [Zaidelman et al., 2020 submitted]. With minor differences, this study used the methodology proposed by Alexander Huth and the linguistic nature of representation within bricoleagues [Huth et al., 2016]. They studied brain representation of the English speech with the help of functional magnetic resonance imaging (fMRI) in seven subjects in response to orally presented narratives. The authors report two results. Firstly, brain mapping of natural language categories on an idealized two-dimensional surface of cortex showed a similarity to the outlines of the Default Mode Network (DMN), a conglomerate of brain structures, which are active in resting state. Secondly, these representations demonstrated broad distribution across the brain with no obvious signs of the initially expected left-sided asymmetry.

Earlier, we applied neurosemantic mapping to Russian-language narratives [Velichkovsky et al., 2020]. We also analyzed in's semantic clusters [Zaidelman et al., 2020 submitted]. In the current work, the issue of laterality of neurosemantic representations will be considered.

METHODS

25 subjects participated in the experiment. Subjects were asked to maintain wakefulness with closed eyes during the study. Stimulus material consisted of five original texts in Russian (1500 wordforms). Each text was a personal story addressing a significant social problem. Participants' involvement in perception and comprehension of stimuli narratives was controlled by a questionnaire and by objective brain imaging data. A professional broadcaster audio recorded the texts, which were presented in a 3T Siemens MRI scanner while whole-brain BOLD signal was continuously registered. The scanning process had two stages: capturing high-resolution anatomical data and recording functional data by a parallel scanning protocol with ultrafast EPI-sequence.

Each word was represented as a 997-dimensional vector. These dimensions (features) were numeric estimations: word2vec distances of a text lexeme to the 997 most frequent Russian nouns and verbs. We evaluated the influence of these features on voxels of individual brains' grey matter over the time of texts presentation. In the next stage of data preparation, we have selected seven participants who were maximally engaged in listening and processing the texts according to the questionnaire and imaging data such as activation of auditory areas, hippocampi and amygdalae related to memory and emotion. Thereafter, a principal component analysis (PCA) on the matrix [Voxels X Features] was performed. The first four components of the PCA scores matrix were used as respective dimensions. The stimulus words were projected into this principal component space by multiplying each word vector by the feature vector in the PCA space. We chose words in this 4D space implying that their connotation was measured by the distance from the center of the word cloud. Within a single step of selection, we have randomly taken 80% of stimulus words and found their convex hull in this space. By repeating this procedure 1000 times, we constructed a set of words that appeared on the hull at least once. In this way, 163 words were selected for further processing. We proceeded with hierarchical clustering of words within the space. After examining the cluster tree diagram, we have selected a cutoff threshold (the maximum distance for words located within the same cluster) equal to 1.

RESULTS

As a result of the final cluster analysis, 12 lexical clusters were obtained with a cardinality varied from 5 to 23 words. The validation of the 12 neurosemantic clusters is their relatively straight-forward interpretation [Zaidelman et al., 2020 submitted]. Indeed, all these clusters were thematically consistent. For example, clusters 2, 4 and 10 were semantically connected to space-and-time of described actions, while clusters 3, 6 and 7 – to topics of threats, overt conflicts, and deprivation. Their names ascribed by a panel of five experts were "city", "event", "space" and "threat", "war", "deprivation", respectively. Notions related to the subjective experience such as "conscious", "intelligence", "feeling", were mapped by the cluster analysis, according to the combined word semantics and brain activity, within the cluster 8, named "experience". Modal lexical frames such as "have to", various action options and goals were concentrated within cluster 9, "goal". The remaining clusters 1, 5, 11 and 12 were related to topics of "rebuilding", "collective", "order", and "try". Note that though the majority of clusters deals with objective circumstances, clusters 3, 7, 9 and 8 also refer to mental states and processes. However, they do it in different ways, which is merely passive suffering, goal-directed planning of action, or reflective contemplation (consciousness) as a part of mental life, correspondingly. In table 1, data for each of seven subjects and for every cluster out of 12 is presented. Number of active voxels in the left (l) and right (r) hemispheres are indicated. As one can see from the table, brain voxel-wise activation seems to be strongly depended both on the neurosemantic clustering and on the individual differences among subjects. For example, the number of active voxels is maximal for cluster "experience" followed by that for clusters "goal" and "war". The pattern of brain lateralization may vary across subjects and clusters. In particular, brain structures for clusters "threat" and "experience" on average showed symmetrical or slight right-sided activation.

Table 1. Number of active voxels for clusters related to subjects and hemisphere.

subj	hemi	rebuilding	city	threat	event	collective	war	deprivation	experience	goal	space	order	try
1254	left	290	458	345	359	341	451	310	469	456	346	383	386
1254	right	326	485	396	387	381	478	328	512	520	345	425	428
1256	left	313	452	396	374	364	496	321	479	478	365	416	401
1256	right	275	399	336	303	296	392	266	444	425	319	322	367
1259	left	350	492	432	445	434	539	361	589	557	377	454	491
1259	right	283	449	375	380	361	491	310	546	491	325	400	424
1265	left	298	446	362	368	365	462	305	472	474	349	382	412
1265	right	271	388	325	320	325	398	269	419	407	307	344	346
1268	left	238	360	283	280	290	369	266	359	362	276	316	306
1268	right	291	434	335	346	360	449	315	424	451	343	354	374
1290	left	322	502	374	393	369	483	329	495	501	393	404	429
1290	right	329	493	464	404	409	572	303	551	516	374	449	430
1297	left	332	487	433	442	398	563	361	560	555	381	458	481
1297	right	309	478	383	380	384	491	306	558	522	358	443	402
mean left		306	457	375	380	366	480	322	489	483	355	402	415
mean right		298	447	373	360	359	467	300	493	476	339	391	396

DISCUSSION

The neurosemantic paradigm is a new approach in the field of cognitive science, which permits investigation of meaningful texts processing and comprehension by healthy subjects in experimental settings. The broad agreement of our findings with those of Huth et al (2016) for the English language points to the universality of the neural organization of lexical mapping and its relative independence of the peculiarities of specific languages. This finding is important by emphasizing the primacy of the shared world we inhabit and experiences we have, over the linguistic idiosyncrasies of individual languages in determining how lexicon is represented in the brain. The discovery of the mechanisms of conceptual processing requires more than simply mapping to cortical and sub-cortical activity. We have argued in a related article [Zaidelman et al., 2020 submitted] that lexical representations of narratives have situational nature. However, the real world is reflected in multiple imaginary worlds that are overtly subjective as are stories in most narratives. It is this subjectivity that makes neurosemantic approach so exciting.

CONCLUSIONS

- 12 lexical clusters were found, with topics expanding from time-and-space of described actions to merely mental states and actions. Clusters "threat" and "experience" were ones that on average demonstrated a symmetrical localization of activated voxels. In other clusters, brain localization had a slight left-sided bias.
- Our results support the view of non-modular and widely distributed nature of semantic representations, which is not limited to structures of left temporal and frontal lobes.
- Our findings were broadly similar to those reported for the English language, which points to the cross-linguistic universality of the principles of lexical mapping in the brain.

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