Multilevel representations of semantics

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To derive a meaningful sentence-level interpretation from serial linguistic input, word semantics need not only to be retrieved but also integrated into a broader event representation. Two current computational models of sentence processing provide contrasting predictions about the timing of integration: Brouwer et al. (Cognitive Science, 2017) model integration as a late process that occurs after activation of meaning specific to the currently perceived word (around 600 ms). On the other hand, Rabovsky et al. (Nature H Behaviour, 2018) propose that a probabilistic event representations is immediately updated within the first 400 ms after onset of an incoming word. In support of the early integration account, a recent MEG study on semantic composition showed evidence for integration as early as 250 ms after hearing a noun (Lyu et al, PNAS, 2019). Importantly, that study relied on the target words inflicting strong semantic constraints on each other (running a program / running a race), leaving open the question of whether early integration also happens in sentences containing more arbitrary combinations of word meanings. To address this question, we created sentences with arbitrary conceptual pairings (electrician cheering / surgeon cheering), pairing nouns with different actions in either agent or patient role without imposing strong semantic constraints. Past fMRI studies using similar stimuli have found event-structure information to be encoded in superior temporal cortex (Frankland & Greene, PNAS, 2015), but lack the temporal resolution necessary to fully describe fast dynamics of language processing.

We will record brain activity from 16 German native speakers using magnetoencephalography (MEG) during passive reading of 192 German sentences for a total of 2 hours (2 sessions). Each sentence is followed by a comprehension question. We analyse source reconstructed neural activity (LCMV beamforming) evoked by the final noun of each sentence. Multivariate representational similarity analysis allows us to track neural patterns encoding semantics on different levels of representation: Using a spatial searchlight, we extract neural patterns for each brain region, for each stimulus and time point and compute the Euclidean distance between those neural pattern vectors for all stimulus pairings. We correlate (Spearman's rank) the resulting trial-by-trial neural dissimilarity matrix (RSM) with different models of our stimuli. Specifically, we will correlate with an event-representation model and a word-representation model. We expect the word-representation model to correlate early after onset up until 400 ms. The temporal dynamics of the comparison with the event-representation model will allow us to test the two predictions with respect to the timing of integration. Statistical inference will be based on nonparametric permutation testing with cluster-based correction across time and space. We base our models for word- and event similarity on behavioural similarity judgments from 200 subjects, which were acquired online using a spatial multi-arrangement task (Kriegeskorte & Mur, Front in Psychology, 2012). Half of the participants performed the task on nouns and the others on sentences (See Figure 1 for results).

By tracking neural representation at different levels of meaning representation, our study will provide a better understanding of compositional processing. We expect the word-similarity model to correlate early after word onset, as the noun identity is retrieved. We will evaluate how long after noun onset the event-similarity model will significantly correlate with the neural pattern and whether these temporal dynamics support either the Brouwer or the Rabovsky language model. In this way, our study will generate evidence for or against alternative (computational) hypotheses of sentence processing, which can in turn inform interpretation of the N400 and P600 ERP components, which are widely used to study language comprehension in the brain.

Nouns				Verbs	
medicine	manual labor	sport	music	communication	physical
Sanitäter *paramedic*	Elektriker *electrician*	Boxer *boxer*	Bassist *bassist*	bestärken *encourage*	stoßen *push*
Internist *internist*	Handwerker *artisan*	Läufer *runner*	Geiger *violin player*	ermuntern *encourage*	schubsen *push*
Pfleger *nurse*	Klempner *plumber*	Sprinter *sprinter*	Musiker *musician*	bejubeln *cheer*	schlagen *beat*
Radiologe *radiologist*	Zimmermann *carpenter*	Athlet *athlete*	Pianist *pianist*	loben *praise*	verscheuchen *chase*
Therapeut *therapist*	Mechaniker *mechanic*	Fußballer *soccer player*	Sänger *singer*	ermutigen *encourage*	verprügeln *beat*
Chirurg *surgeon*	Tischler *carpenter*	Sportler *sportsman*	Gitarrist *gitarrist*	trösten *comfort*	schütteln *shake*

Table 1: *Full list of vocabulary (English translation in italics). Stimuli consist of 48 unique propositions derived from 24 nouns (4 thematic categories) and 12 verbs (2 thematic/valence categories). Each proposition will be presented in active an passive form. Each noun appears in object and subject positions and each sentence is repeated once during the experiment.*

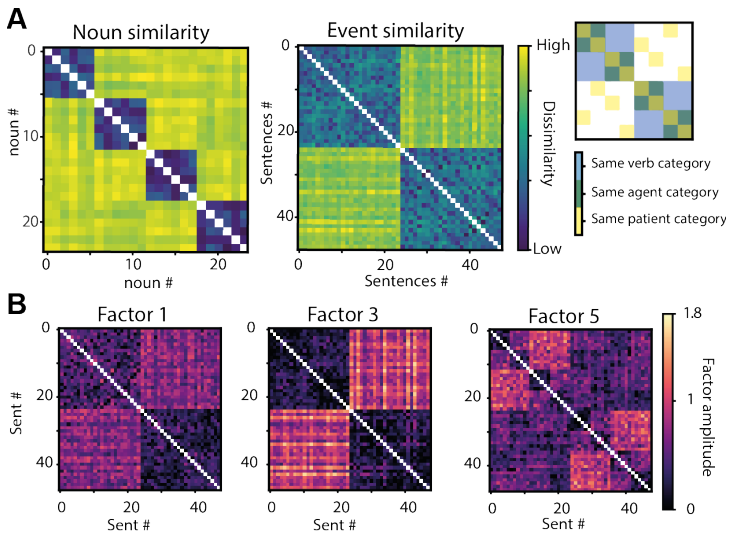

Figure 1: *(A) Mean RSMs based on SMA (n=100). For the noun model, words order is according to thematic category. Mean RSMs show, perceived event similarity is mainly driven by verb semantics (middle). Expected event similarities are indicated by cartoon (right).(B) Nonnegative matrix factorisation further reveals subtle differentiation in most participants, indicating inter-individual differences that could be related to inter-individual differences in brain activity. Factor loadings per item pair shown for 3 Factors.*

1	Heute Morgen lobte der Sanitäter den Elektriker. *This morning the paramedic praised the electrician*
2	Heute ermutigte der Chirurg einen Tischler. *Today the surgeon encouraged the carpenter*
3	Vorhin verscheuchte der Zimmermann den Elektriker. *Earlier the carpenter chased the electrician away*
4	Gestern schlug der Fußballer einen Boxer. *Yesterday the soccer player hit the boxer.*

Table 2: *Example sentences. 1 and 2 are considered most similar because thematic categories of agent, patient and verb are shared. 1 and 3 are more dissimilar in comparison, since verbs are of different thematic category, regardless of final noun identity. 1 and 4 are most dissimilar since they do not share any semantic cateogry.*

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German word order. We make use of the flexible word order in German to ensure unambiguous assignment of semantic roles when the subject noun is being read. We use verb-second word order ("Yesterday called the nurse the plumber"), which moves the verb before the subject noun, such that the agent/patient identity can be disambiguated before the word is read and therefore binding can occur immediately when the word is presented as opposed to the more frequent SVO order, for which semantic roles are only disambiguated after the main verb.