Brain & Language 168 (2017) 57–72

Contents lists available at ScienceDirect

Brain & Language

journal homepage: www.elsevier.com/locate/b&l

Task-dependent neural and behavioral effects of verb argument structure features

Svetlana Malyutina[a,b,*], Dirk-Bart den Ouden[b]

[a] National Research University Higher School of Economics, Staraya Basmannaya Street 21/4, Room 510, 105066 Moscow, Russia
[b] University of South Carolina, Department of Communication Sciences and Disorders, 915 Greene Street, 29208 Columbia, SC, USA

ARTICLE INFO

Article history:
Received 15 October 2015
Revised 7 September 2016
Accepted 17 January 2017

Keywords:
Verbs
Verb argument structure
Thematic roles
Subcategorization options
Semantic complexity
Task-dependent effects
fMRI

ABSTRACT

Understanding which verb argument structure (VAS) features (if any) are part of verbs' lexical entries and under which conditions they are accessed provides information on the nature of lexical representations and sentence construction. We investigated neural and behavioral effects of three understudied VAS characteristics (number of subcategorization options, number of thematic options and overall number of valency frames) in lexical decision and sentence well-formedness judgment in healthy adults. VAS effects showed strong dependency on processing conditions. As reflected by behavioral performance and neural recruitment patterns, increased VAS complexity in terms of subcategorization options and thematic options had a detrimental effect on sentence processing, but facilitated lexical access to single words, possibly by providing more lexico-semantic associations and access routes (facilitation through complexity). Effects of the number of valency frames are equivocal. We suggest that VAS effects may be mediated semantically rather than by a dedicated VAS module in verbs' representations.

1. Introduction

Verbs occupy a pivotal role in sentence construction. They determine the number of arguments that appear in a sentence, their thematic roles (agent, theme, etc.), grammatical roles (subject, direct object, etc.) and grammatical class realizations (noun phrase, prepositional phrase, dependent clause, etc.). Within the lexicalist (or projectionist) framework, the *argument structure hypothesis* suggests that information on verb argument structure (VAS) is stored in the lexicon (Boland & Blodgett, 2006; Rappaport Hovav & Levin, 1998) and "projected" from there into sentence structures. VAS information automatically becomes available, i.e., is exhaustively accessed, upon activation of the verb. Alternatively, according to the constructivist approach, VAS may simply be induced from the lexical meaning of verbs, without a need for separate storage (e.g., Hale & Keyser, 2002). Such accounts predict that VAS information only plays a role when it is relevant, i.e., its activation depends on the context of verb use. Still, even within the lexicalist framework, it is a matter of debate which characteristics exactly are part of lexically stored VAS representations.

Because VAS processing plays out at the interface of grammar and lexicon, evidence on the neural correlates of VAS processing is directly relevant to current neurobiological models of language processing, such as the dorsal-ventral dual-route models proposed by Hickok and Poeppel (2004, 2007), Friederici (2011), and Bornkessel-Schlesewsky and Schlesewsky (2013). Neural bases of VAS processing can provide insights into the distribution of grammatical and lexico-semantic processes in the brain and possibly on how the interaction between the two is implemented neurally. In the present paper, we will interpret neural correlates of processing specific VAS characteristics in light of previously proposed general neurolinguistic models.

Besides the importance for general models of lexical representations and sentence construction, understanding whether or which VAS features are part of verbs' lexical entries also has clinical relevance. Due to the central role of verbs in sentence processing, many successful treatments of sentence production and comprehension in agrammatic aphasia are centered around verbs, training the ability to access VAS information and/or map it onto syntactic structures (Bazzini et al., 2012; Marshall, 1995; Rochon, Laird, Bose, & Scofield, 2005; Thompson, Riley, Den Ouden, Meltzer-Asscher, & Lukic, 2013). Such verb-based treatments can be further informed by VAS research in several ways. First, approaches that sequence treated stimuli in the order of increasing (Bazzini et al., 2012) or decreasing (Thompson et al., 2013)

---

* Corresponding author at: Staraya Basmannaya Street 21/4, Room 510, 105066 Moscow, Russia.

E-mail addresses: smalyutina@hse.ru (S. Malyutina), denouden@sc.edu (D.-B. den Ouden).

http://dx.doi.org/10.1016/j.bandl.2017.01.006

complexity will benefit from evidence on which VAS characteristics affect processing complexity. Then, evidence on VAS effects under various processing conditions can inform the choice of most efficient tasks to tap into VAS retrieval. It can suggest whether tasks need to be focused on syntactic structure (Thompson et al., 2013), or verb semantics (Edmonds, Nadeau & Kiran, 2009), or whether retrieval of isolated verbs may provide sufficient exposure to VAS. Lastly, research on the neural bases of VAS processing may suggest targets for brain stimulation treatments of verb and/or sentence processing in aphasia (Cappa, Sandrini, Rossini, Sosta, & Miniussi, 2002; Fertonani, Rosini, Cotelli, Rossini, & Miniussi, 2008; Marangolo et al., 2013), as well as inform pre-surgical language mapping, where verb tasks seem more promising than noun tasks (Havas et al., 2015).

So far, most studies on VAS have focused on effects of the verb's valency (number of arguments), whereas data on other VAS characteristics and, importantly, on how VAS access is modulated by processing conditions, are limited. The current study used functional neuroimaging and behavioral experiments to assess the processing load associated with three VAS features that have hitherto been relatively understudied: the number of subcategorization options, number of thematic-role options and number of valency frames. Below, we outline previous evidence on neural and behavioral effects of individual VAS characteristics in healthy speakers and show that most effects are still inconclusive and need more research in light of processing conditions.

1.1. Valency

The verb's valency refers to the number of arguments that are used with the verb in a sentence and represent participants of the corresponding action. For example, intransitive verbs have only one argument (*Jack laughs*), transitive verbs have two arguments (*Jack calls Anna*), and ditransitive verbs have three arguments (*Jack gives Anna a present*). Verbs with higher valency (i.e., greater number of arguments) typically impose a greater processing cost, as demonstrated in both single-word-level tasks (e.g., naming: Malyutina & Den Ouden, 2015) and sentence-processing tasks (e.g., cross-modal lexical decision interference: Ahrens & Swinney, 1995; Shapiro, Brookins, Gordon, & Nagel, 1991). However, other studies show behavioral facilitatory or null effects of increased valency (Assadollahi, Meinzer, Flaisch, Obleser, & Rockstroh, 2009; Malyutina & Den Ouden, 2015; Rodriguez-Ferreiro, Llorenc, & Sanz-Torrent, 2014; Thompson, Bonakdarpour, & Fix, 2010; Thompson et al., 2007). It is noteworthy that such studies have generally employed shallow processing tasks, such as lexical decision. Such tasks may not require exhaustive access to all VAS components, in contrast with tasks that induce deeper processing.

In neuroimaging studies, the processing of verbs with higher valency, even in single-word tasks, is typically associated with increased neural activation in a network of left temporal and parietal regions, such as posterior temporal, angular and supramarginal gyri (Den Ouden, Fix, Parrish, & Thompson, 2009; Meltzer-Asscher, Mack, Barbieri, & Thompson, 2015; Thompson et al., 2007; Thompson et al., 2010), rather than exclusively with areas traditionally associated with syntactic processing, such as Broca's area. However, Hernandez, Fairhall, Lenci, Baroni, and Caramazza (2014) used a lexical decision task and found an effect in the opposite direction: stronger frontal and temporal activation for intransitive than transitive verbs, possibly due to greater prototypicality of transitive predicates and general task-specificity of valency effects.

Overall, both neuroimaging and behavioral findings suggest that valency information is stored as part of the verb's lexical entry. It is accessed exhaustively upon lexical activation even under conditions when no sentence context drives direct activation of all arguments. Task-dependent patterns suggest that the effect of valency may be modulated by processing conditions.

1.2. Subcategorization options

The verb's subcategorization options are the possible morphosyntactic realizations of its arguments. For example, some transitive verbs only attach noun phrases as their second argument (*He completed the work* / **He completed that*. . .), whereas others may be complemented by either noun phrases or dependent clauses (*He forgot the poem* / *He forgot that he had an appointment*). Early behavioral work demonstrated that verbs allowing a greater number of subcategorization options come at a greater processing cost, even when used in the same type of syntactic structure as verbs with a lower number of subcategorization options (in paraphrasing and anagram solution tasks: Fodor, Garrett, & Bever, 1968; rapid visual presentation comprehension: Holmes & Forster, 1970; time-compressed speech comprehension: Chodorow, 1979). However, later experiments did not replicate this effect (secondary task during sentence processing: Shapiro, Zurif, & Grimshaw, 1987; lexical decision and word-class judgment: Rodriguez-Ferreiro et al., 2014).

In neuroimaging research, Shetreet, Palti, Friedmann, and Hadar (2007) found that processing sentences that contain verbs with a greater number of subcategorization options was associated with increased activation in the left superior temporal gyrus and inferior frontal cortex (BA 9, 47). In Shetreet, Friedmann, and Hadar (2010), processing of subcategorization options (or, in their terminology, 'complementation frames') was also associated with the left superior temporal gyrus.

Overall, most previous research indicates that subcategorization options are exhaustively accessed in verb processing. However, most evidence comes from sentence-level tasks and it is of interest whether the effect holds in single-word processing.

1.3. Number of thematic options

VAS may also entail information on thematic roles of the verb's arguments. For example, the argument of the intransitive verb '*to break*' has the thematic role of *patient* (i.e., a "passive" participant that the action is happening to; *The glass broke*), whereas the argument of the intransitive verb '*to run*' has the thematic role of *agent* (i.e., an active participant executing the action; *The boy is running*). The thematic role of patient is less common or "canonical" for the subject position than the thematic role of agent and possibly involves syntactic movement of the verb argument from its original object position (where it is generated as the complement of the verb) to the subject (specifier) position in the syntactic structure (Levin & Rappaport-Hovav, 1994).

A lexical-decision fMRI study by Meltzer-Asscher, Schuchard, Den Ouden, and Thompson (2013) addressed thematic roles by contrasting alternating-transitivity verbs (e.g., '*to break*', '*to boil*') with non-alternating unergative verbs (e.g., '*to run*'). Alternating verbs were associated with increased activation in bilateral angular and supramarginal gyri, middle and superior temporal and middle and superior frontal gyri. However, the experimental design did not tease apart whether the effect was indeed due to the more complex (non-canonical) thematic role assignment by alternating verbs, or to the greater number of valency frames of alternating verbs (see Section 1.4). Meltzer-Asscher et al. (2015) contrasted unaccusative verbs to non-alternating transitive and unergative verbs in lexical decision and found that thematic role complexity (non-canonicity) was associated with greater activation in the left precentral and inferior frontal gyri. More research is warranted to isolate the effects of the number of thematic options and valency frames.

1.4. Number of valency frames

Verbs can have multiple possible argument structure frames (alternations) that differ on all or some of the above VAS characteristics. For example, the verb '*to donate*' may be used in at least two frames (*She donated the clothes; She donated the clothes to the church*) that differ in the number of arguments and, consequently, in thematic roles and subcategorization options. It is possible that the number of alternations between VAS frames is the most important factor affecting the cost of verb processing (Ramchand, 2014; Shetreet, 2014), whereas any VAS characteristics of any individual frame (e.g., the type of thematic roles in the one-argument frame, the maximum number of arguments, etc.) play a smaller role.

As discussed above, experiments by Meltzer-Asscher et al. (2013, 2015) did not separate the number of thematic roles from the number of valency frames. Only a limited number of studies have specifically manipulated the number of valency frames in isolation from other VAS properties. Early work by Shapiro et al. (1987) and Shapiro, Zurif, and Grimshaw (1989) found a detrimental behavioral effect of a greater number of valency frames in a secondary task during sentence comprehension, although this was not replicated by Ahrens and Swinney (1995).

In neuroimaging research, Shetreet et al. (2007) performed a parametric analysis of verbs that differed not only in the number of subcategorization options (see above) but also in the number of valency frames ("number of thematic options", in their terminology). They found that a greater number of valency frames was associated with increased activation in the left superior temporal and inferior frontal (BA 9, 47) gyri. But this could be driven by differences between verb groups in terms of subcategorization options rather than valency frames. Shetreet et al. (2010) contrasted "optional" verbs (e.g., *to eat*, which may come either with or without a noun phrase complement) to verbs that have two subcategorization frames but only one valency frame (e.g., *to discover*, which may come either with a noun phrase or with a clause complement) and found different results depending on the syntactic context. When optional verbs were presented with a complement, a lower number of valency frames was associated with increased activation in left superior temporal, middle temporal and middle frontal gyri. When the same verbs were presented without a complement, a lower number of valency frames was associated with increased activation in a bilateral frontal and parietal network. This suggests that access to valency frames may be guided by context.

Overall, there is no evidence of a robust neural or behavioral effect of the number of valency frames, contrary to early findings by Shapiro et al. (1987, 1989). Nevertheless, context-dependent results by Shetreet et al. (2010) again indicate that VAS is not accessed uniformly across linguistic contexts. Thus, further research needs to shed light on task effects that may account for seemingly mixed findings.

1.5. Summary and research hypotheses

Among VAS characteristics addressed by previous research, the findings appear the most robust for valency, suggesting that it is lexically stored and exhaustively accessed in verb processing. Data on other VAS properties are less conclusive and warrant more research with designs that carefully isolate each property. In addition, there is an emerging pattern of dependency of VAS effects on linguistic context and task. This calls for a systematic investigation of VAS characteristics under various processing conditions, as also emphasized by Meltzer-Asscher et al. (2015).

In our series of experiments we isolated the number of subcategorization options, the number of thematic options, and the number of valency frames, and investigated how VAS access is modulated by processing conditions. We conducted two neuroimaging experiments (Experiment 1, using a sentence task, and Experiment 2, using a single-word task) and one behavioral experiment (Experiment 3, including both a sentence and a single-word task). Previous research suggests that VAS access depends on the processing conditions: e.g., whether the comprehender needs to integrate a verb into a specific sentence context where a particular VAS frame is selected vs. whether they need to process isolated words outside a restrictive context.

Although we apply caution with respect to potential circularity of function-location-mapping arguments, specific locations of brain activations may suggest the nature of any increased load associated with VAS characteristics. Following both the neurocognitive model of VAS processing by Thompson and Meltzer-Asscher (2014) and broader neuroimaging literature on language processing, we hypothesized that activation in left posterior perisylvian regions such as left posterior superior temporal, posterior middle temporal, angular and supramarginal gyri (Binder, Desai, Graves, & Conant, 2009; Thompson & Meltzer-Asscher, 2014) and in pars orbitalis of inferior frontal gyrus (Binder et al., 2009; Bookheimer, 2002; Gold & Buckner, 2002) would reflect lexical storage/retrieval demands. Activation in pars triangularis and opercularis of the left inferior frontal gyrus, previously associated with structure building and ordering (Friederici & Kotz, 2003; Meyer, Obleser, Kiebel, & Friederici, 2012; Thompson & Meltzer-Asscher, 2014), was assumed to reflect greater integration/structure building demands.

2. Experiments

2.1. Experimental design

All three experiments used the same design with respect to verb types. VAS was characterized in terms of the verbs' number of subcategorization options, overall number of thematic options and overall number of valency frames. Four verb groups were used (see Table 1). Group 1 (*complete*-verbs) had only one valency frame (used only transitively) and only one subcategorization option (only used with noun phrases and no other grammatical categories). Group 2 (*demand*-verbs) also had only one valency frame (only used transitively) but, unlike *complete*-verbs, had multiple subcategorization options (used with either a noun phrase or at least one other subcategorization option, such as an infinitive and/or a dependent clause). Group 3 (*sing*-verbs) had two valency frames (used both intransitively and transitively) but only one frame for thematic role assignment (i.e., the role of the first argument did not differ between the transitive and intransitive use: e.g., both in *The lady sang a song* and *The lady sang* the subject noun phrase '*the lady*' has the thematic role of agent). This group corresponds to verbs undergoing unspecified object alternation (Levin, 1993). Group 4 (*break*-verbs) had two valency frames (used both intransitively and transitively) but, unlike *sing*-verbs, also had two thematic-role options (i.e., the role of the first argument differed between the transitive and intransitive use: e.g., the thematic role of the subject noun phrase '*the man*' is different in '*The man accelerated*' and '*The man accelerated the vehicle*'). This group corresponds to verbs undergoing the inchoative-causative alternation (Levin, 1993). Verbs were selected based on judgement by both authors (both linguists) on whether the verbs fulfill the above criteria (see Appendix A for linguistic examples that verb inclusion was based on).

The study design allowed us to investigate several VAS properties by contrasting different verb groups: (1) the contrast of *demand*-verbs versus *complete*-verbs yields activity associated with processing subcategorization options; (2) the contrast of *break*-verbs versus *sing*-verbs yields activity associated with thematic

Table 1
VAS characteristics of the four verb groups used in all experiments.

Verb Group	Maximum number of arguments	Number of valency frames	Number of thematic options	Number of subcategorization options
complete	2	1	1	1
demand	2	1	1	⩾2
sing	2	2	1	(⩾2, across valency frames)
break	2	2	2	(⩾2, across valency frames)

options; (3) the contrast of *sing*-verbs versus *complete*-verbs yields activity associated with valency frames.[1]

2.2. Experiment 1: Neural correlates of VAS processing in a sentence-level task

2.2.1. Method

2.2.1.1. Participants. Seventeen college-age volunteers participated in the study (10 females; mean age 23.4, range 20–29). All were right-handed native speakers of English with normal or corrected-to-normal vision and no history of neurological or speech-language disorders. All participants gave informed consent prior to the experiment, in accordance with the Helsinki declaration. For two participants, one of the four scanning runs was excluded from the final analysis for technical reasons.

2.2.1.2. Task. Participants were instructed to silently read sentences and to press a button if a sentence was not well-formed (not grammatical or not meaningful), while not pressing any buttons for well-formed sentences. The task involved no motor response for experimental trials, in order to eliminate any motor activity that might contaminate condition-related brain activity.

2.2.1.3. Design and stimuli. Experimental stimuli were sentences that included 20 verbs from each of the four experimental groups (see Section 2.1), used twice each, for a total of 160 sentences. All sentences had the same structure, consisting of a subject noun phrase, a verb predicate in the past tense and an object noun phrase (e.g., *The user completed the survey; The buyer demanded a refund*). Conditions were matched on the overall sentence length in the number of words and syllables. Between conditions, verbs were matched for frequency (Baayen, Piepenbrock, & Gulikers, 1995), length in syllables and letters, and imageability (Coltheart, 1981), while object and subject nouns were matched for frequency (Baayen et al., 1995), imageability (Coltheart, 1981), number of singular/plural nouns, and number of animate/inanimate nouns (Table 2).

Additionally, since the task was to judge the well-formedness of sentences, stimuli included 80 not-well-formed filler sentences: forty "syntactic fillers" had syntactic violations, i.e., included an intransitive verb followed by a direct object (e.g., *The sailor laughed the weather*), and forty "semantic fillers" included semantic violations (e.g., *The test adored the flaws*). Two types of fillers were used to ensure that participants attended to both grammar and meaning. Although fillers were not included in the analysis, they were matched to experimental sentences on all properties listed above. Some of the verbs were repeated within fillers as well as across fillers and experimental sentences so that participants could not strategically judge sentences based on whether they included a repeated verb.

2.2.1.4. Procedures. After instructions and out-of-scanner practice, participants were scanned with a 3.0 T Siemens Tim Trio system. A T1-weighted anatomical MRI brain scan was obtained first (TR 2250 ms, TE 4.52 ms, 256 × 256 matrix, 256 × 256 FOV, slice thickness 1 mm, 176 axial slices), followed by four runs of T2*-weighted multi-band EPI functional scanning (TR 1550 ms, TE 34 ms, 86 × 86 matrix, 215 × 215 FOV, slice thickness 2.5 mm, 42 axial slices, 295 volumes). Functional runs were event-related and each included 60 trials. In each trial, a stimulus sentence was presented on a screen for 3 s with varying inter-stimulus interval (mean 4.5, range 3.0–11.8 s) during which a fixation cross was presented. Each run lasted about 7.5 min. Sequencing of conditions and selection of inter-stimulus intervals were optimized using the Optseq software (http://surfer.nmr.mgh.harvard.edu/optseq/). The run order was ABCD for half of participants and DCBA for the other half. After each run, participants were given automated feedback on their percentage of accurate responses for that run. E-Prime 2.0 software (http://www.pstnet.com/eprime.cfm) was used for stimuli presentation and recording of the responses.

2.2.1.5. Data analysis. fMRI data were analyzed in SPM8 (http://www.fil.ion.ucl.ac.uk/spm/software/spm8). Preprocessing included slice-acquisition timing correction, realignment of the anatomical scans to the mean functional volume, normalization of anatomical and functional scans to the MNI 152-subject template brain using unified segmentation normalization, and spatial smoothing with an 8 mm FWHM isotropic Gaussian kernel. No participants were excluded from further analysis due to excessive motion (greater than 3 mm in any direction).

In the first-level statistical analysis, a high-pass filter of 128 s was used to eliminate scanner drift. For each run, seven conditions were modeled (four experimental conditions, two filler conditions and errors as a separate condition). Six movement parameters obtained in re-alignment were entered as regressors. A canonical hemodynamic response function with a time derivative was used to model BOLD response to stimuli. Participants' binary brain images (binarized sum of gray and white matter images obtained during segmentation) were used as masks for inclusion of relevant voxels into the analysis. Individual participants' summary activation maps for four experimental conditions were entered into a second-level repeated-measures ANOVA with experimental condition as an independent variable. Three a priori planned paired *t*-tests were performed for contrasts described in Section 2.1. Monte Carlo simulation in AlphaSim (http://afni.nimh.nih.gov/pub/dist/doc/program_help/AlphaSim.html) yielded a cluster-size threshold of 17 contiguous voxels (459 mm^3) to correct for multiple comparisons at $\alpha = 0.05$ with a voxelwise threshold of $\alpha = 0.001$ (Forman et al., 1995; Friston, Worsley, Frackowiak, Mazziotta, & Evans, 1994). Anatomic labeling of activation clusters was performed using the Automated Anatomical Labeling atlas and toolbox (Tzourio-Mazoyer et al., 2002).

---

[1] It may appear that the number of valency frames could be investigated by contrasting *sing*-verbs to *demand*-verbs (rather than to *complete*-verbs). However, *sing*- and *demand*-verbs differ not only in the number of valency frames but also in the number of subcategorization options within their two-argument frames (in the two-argument frame, *demand*-verbs have two subcategorization options and *sing*-verbs have one subcategorization option). Thus, any difference between *sing*- and *demand*-verbs could actually result from an effect of subcategorization options, whereas only one valency frame is in fact accessed. A contrast of *sing*-verbs versus *complete*-verbs is more appropriate because these two groups both have only one subcategorization frame within each valency frame. Thus, any difference found between *sing*- and *complete*-verbs would necessarily indicate that multiple valency frames are accessed (multiple subcategorization frames may be accessed too, but only as a consequence of accessing multiple valency frames).

Table 2
Matching of experimental conditions, mean (SD).

		complete-verbs	*demand*-verbs	*sing*-verbs	*break*-verbs	Semantic fillers	Syntactic fillers
Verb properties	Frequency	1.5 (0.4)	1.6 (0.4)	1.5 (0.6)	1.6 (0.6)	1.6 (0.6)	1.6 (0.5)
	Length, syllables	2.0 (0.7)	2.0 (0.5)	2.0 (0.8)	1.9 (0.9)	1.9 (0.8)	2.0 (0.7)
	Lengths, letters	6.7 (1.6)	6.7 (1.4)	6.1 (2.1)	6.2 (2.1)	6.2 (1.7)	6.5 (1.2)
	Imageability	403.9 (69.8)	400.5 (57.6)	409.2 (93.0)	402.2 (65.3)	403.2 (99.4)	405.2 (107.7)
	Orthographic neighborhood size	0.9 (1.1)	1.6 (3.6)	2.9 (4.3)	2.6 (2.7)	2.3 (3.6)	1.2 (1.7)
Sentence task only							
Subject noun properties	Frequency	1.6 (0.6)	1.6 (0.7)	1.7 (0.7)	1.6 (0.7)	1.6 (0.7)	1.6 (0.6)
	Imageability	541.4 (72.4)	538.1 (70.5)	538.1 (59.0)	531.5 (65.3)	541.0 (62.7)	539.6 (72.2)
	Number of plural	4/40	4/40	4/40	5/40	5/40	3/40
	Number of animate	31/40	31/40	32/40	31/40	31/40	31/40
Object noun properties	Frequency	1.7 (0.6)	1.7 (0.6)	1.7 (0.7)	1.7 (0.7)	1.6 (0.5)	1.6 (0.7)
	Imageability	541.4 (72.4)	538.1 (70.5)	538.1 (59.0)	531.5 (65.3)	503.8 (97.8)	541.0 (62.7)
	Number of plural	7/40	6/40	5/40	8/40	3/40	8/40
	Number of animate	8/40	8/40	8/40	8/40	8/40	7/40
Sentence properties	Length, words	5.0 (0.0)	5.0 (0.0)	5.0 (0.0)	5.0 (0.0)	5.0 (0.0)	5.0 (0.0)
	Length. syllables	8.2 (1.6)	8.1 (1.4)	8.1 (1.4)	8.1 (1.9)	8.2 (1.5)	8.2 (1.4)

Frequency: Baayen et al. (1995). Imageability: Coltheart (1981). Orthographic neighborhood size: Medler and Binder (2005).

Table 3
AAL regions. MNI coordinates. Cluster size and maximal t-values for activation clusters in Experiment 1 (voxelwise p < 0.001; cluster size (k) > 17). *L* – left, *R* – right, *bil.* – bilateral; *ant.* – anterior, *inf.* – inferior, *mid.* – middle, *post.* – posterior, *sup.* - superior. Mean (across-participant) contrast values relative to baseline were obtained with the MarsBaR toolbox in SPM (Brett, Anton, Valabregue, & Poline, 2002).

L/R	Activation peak	Cluster extent	*x*	*y*	*z*	k	*t*-Max	*Mean contrast value*	
Greater number of subcategorization options (demand-verbs > complete-verbs)								*demand*	*complete*
L	Post. cingulum	Precuneus, mid. cingulum	−12	−49	−28	172	6.76	0.30	−2.88
L	Angular gyrus	Mid. temporal gyrus, sup. temporal gyrus, supramarginal gyrus	−54	−61	25	132	6.71	0.80	−2.00
L	Mid. temporal gyrus	Sup. temporal pole	−60	−40	1	190	6.17	5.79	3.71
L	Sup. medial frontal gyrus	Sup. frontal gyrus	−9	56	28	70	5.22	0.66	−1.32
bil.	Thalamus	Bil. thalamus, R caudate nucleus, R pallidum	−9	−31	4	165	4.85	4.35	2.35
R	Cerebellum	–	6	−49	−44	19	4.53	4.68	2.80
R	Cerebellum	–	30	−55	−38	29	4.48	2.96	1.55
R	Mid. temporal gyrus	Sup. temporal gyrus	45	−34	−2	29	4.48	3.92	2.16
R	Sup. temporal gyrus	Mid. temporal gyrus	54	−10	−14	19	4.30	3.31	1.47
R	Calcarine gyrus	Lingual gyrus, inf. occipital gyrus, fusiform gyrus	21	−91	−2	31	4.11	18.70	16.62
Lower number of subcategorization options (complete-verbs > demand-verbs)									
	None								
Greater number of thematic options (break-verbs > sing-verbs)								*break*	*sing*
L	Mid. cingulum	–	−6	−4	28	35	4.46	2.56	0.71
L	Caudate nucleus	–	−18	−7	22	41	3.94	0.26	−1.17
L	White matter underlying pars orbitalis/triangularis of the left inf. frontal gyrus		−27	35	4	20	3.89	1.70	0.56
Lower number of thematic options (sing-verbs > break-verbs)								*sing*	*break*
R	Angular gyrus	Mid. temporal gyrus, sup. temporal gyrus	51	−64	25	25	3.70	−1.40	−2.69
Greater number of valency frames (sing-verbs > complete-verbs)									
	None								
Lower number of valency frames (complete-verbs > sing-verbs)								*complete*	*sing*
L	Sup. frontal gyrus	Supplementary motor area	−15	8	46	31	4.94	2.39	1.54

2.2.2. Results

2.2.2.1. Behavioral results. Participants performed well on the task (mean accuracy 94.8%, range 90.4–99.2%). The mean reaction time was 1902 ms (range 1628–2156 ms). Reaction time data were only collected for filler items, as experimental stimuli required no response.

2.2.2.2. Whole-brain fMRI analysis. A full list of all activation clusters for this and further comparisons in Experiment 1 is presented in Table 3, and all significant differential activation patterns are illustrated in Fig. 1.

2.2.2.2.1. Number of subcategorization options. The paired *t*-test analysis of *complete*-verbs vs. *demand*-verbs revealed clusters of increased activation associated with a greater number of subcategorization options in the left angular and supramarginal gyri, left posterior middle temporal gyrus, frontal superior and superior medial gyri, left precuneus and posterior cingulate gyrus, several subcortical structures, including left and right thalamus and the right cerebellum. There was no significantly increased activation associated with a lower number of subcategorization options.

2.2.2.2.2. Number of thematic options. The paired *t*-test analysis of *break*-verbs vs. *sing*-verbs revealed clusters of increased activation

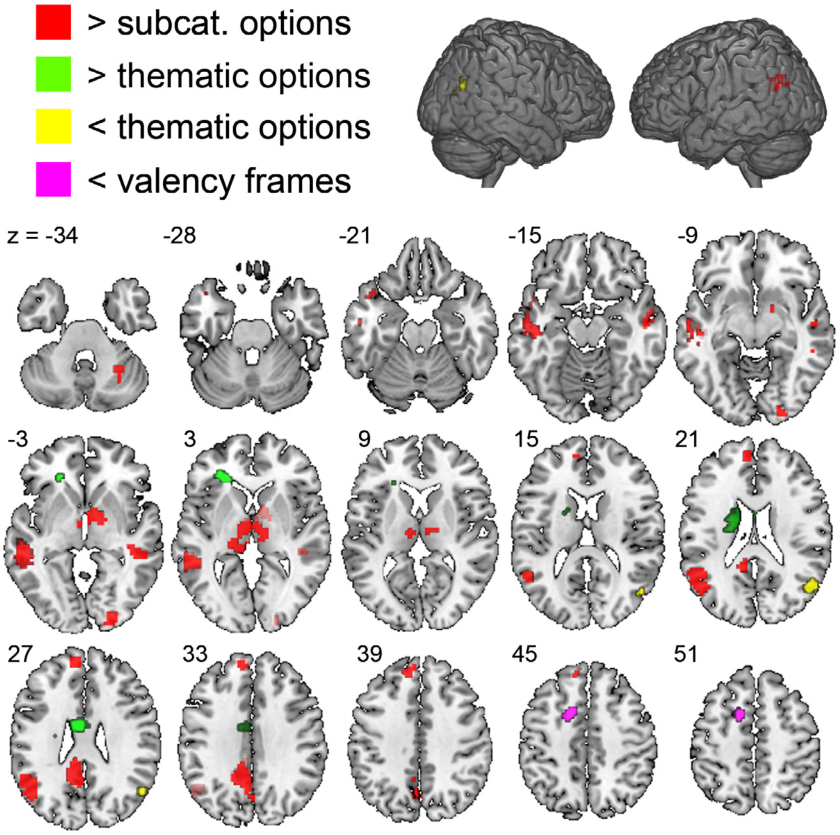

Fig. 1. Differential activation clusters in Experiment 1 (voxelwise $p < 0.001$; cluster size $(k) > 17$). Red = Greater number of subcategorization options (*demand*-verbs > *complete*-verbs); Green = Greater number of thematic options (*break*-verbs > *sing*-verbs); Yellow = Lower number of thematic options (*sing*-verbs > *break*-verbs); Violet: Lower number of valency frames (*complete*-verbs > *sing*-verbs).

associated with a greater number of thematic options in white matter underlying left inferior frontal gyrus, in left caudate nucleus and left middle cingulum. The opposite contrast showed areas of increased activation associated with a lower number of thematic options at the junction of the right angular, superior temporal and middle temporal gyri.

2.2.2.2.3. Number of valency frames. The paired *t*-test analysis of *sing*-verbs vs. *complete*-verbs did not reveal any increased activation associated with a greater number of valency frames. The opposite contrast revealed a cluster of increased activation associated with a lower number of valency frames in the left superior frontal gyrus and supplementary motor area.

2.2.3. Summary

Experiment 1 used fMRI to investigate the neural correlates of three VAS characteristics in a sentence processing task. All verbs were used in the same syntactic context to ensure that any neural effects reflect VAS processing rather than the processing of the sentential context. The analysis revealed areas of increased activation for more complex verbs for two out of three investigated VAS characteristics: the number of subcategorization options (left superior frontal gyrus and temporo-parietal junction extending to the posterior middle temporal gyrus) and the number of thematic options (left cingulum and white matter underlying left inferior frontal gyrus), but not the number of valency frames. Unexpectedly, the analysis also found areas of increased activation for *less* complex verbs for two out of three VAS characteristics: the number of thematic options (right angular gyrus) and the number of valency frames (left superior frontal gyrus), but not the number of subcategorization options.

2.3. Experiment 2: Neural correlates of VAS processing in a single-word-level task

2.3.1. Method

2.3.1.1. Participants. Twenty-one college-age participants participated in the study (12 females; mean age 22.9, range 19–30). All were right-handed native speakers of English with normal or corrected-to-normal vision and no history of neurological or speech-language disorders. All participants gave informed consent prior to the experiment, in accordance with the Helsinki declaration.

2.3.1.2. Task. The task was to silently read strings of letters presented on the screen and to press one button if a string of letters made a real English word or another button if it did not. Note that unlike Experiment 1, Experiment 2 included a motor response for both fillers (non-words) and experimental stimuli (real words). Our reasoning for having this difference between the two tasks, rather than formally matching them on the response requirements, was as follows. Non-words “stand out” compared to real words to a greater extent than ill-formed sentences compared to well-formed sentences, where judgments are often less categorical and more gradient. Thus, a low number of non-words might alter visual word recognition (making it an easier and shallower task) in a way that would not occur in sentence processing. For this reason, we chose to have a higher ratio of fillers (non-words) in the lexical decision task compared to the number of fillers (ill-formed sentences) in the sentence task. As a consequence, we deemed it necessary to add an overt response to real words in the lexical decision task, in order to avoid extra response inhibition for real words as a more numerous type of stimuli. We return to the response difference between the two experiments in the Discussion section, below.

2.3.1.3. Design and stimuli. Stimuli included 20 verbs from each group (see Section 2.1), for a total of 80 verbs, each repeated twice, and 120 pronounceable non-words, each repeated twice. All stimuli were preceded by "*to*" (e.g., "*to break*" rather than "*break*") to ensure their unambiguous interpretation as verbs. Verb groups were matched for frequency (Baayen et al., 1995), length in syllables and letters, orthographic neighborhood size (Medler & Binder, 2005) and imageability (see below). Non-words, formed by re-combining pronounceable segments of experimental verbs, were matched to experimental verbs on length in syllables and letters and on orthographic neighborhood size (Medler & Binder, 2005).

To assess imageability specific to verbs (rather than for word forms across word classes, as in existing databases), we conducted an online survey where stimuli were presented with a verb particle "*to*" and participants were specifically asked to assess the imageability of an action on a scale from 1 (not imageable) to 7 (highly imageable). Since most verbs intended for use in Experiments 1 and 2 have relatively abstract semantics, the survey included 10 highly imageable fillers (e. g., "*to kiss*", "*to swim*"). The survey was completed by 45 native speakers of English (43 females; mean age 28.0, range 22–52 y.o.) with no reported history of neurological or speech- language disorders. The results were used to match experimental conditions.

2.3.1.4. Procedures. Scanning procedures were identical to those in Experiment 1 (Section 2.2.1.4), with four fMRI runs each consisting of 327 volumes. Functional runs were event-related and each included 100 items presented for 1.5 s with varying inter-stimulus intervals (mean 3.5, range 1.5–11.1 s) during which a fixation cross was presented. Each run lasted about 8.75 min. Sequencing of conditions and selection of inter-stimulus intervals were optimized using Optseq (http://surfer.nmr.mgh.harvard.edu/optseq/). The run order was ABCD in half of participants and CDAB in the other half of the participants. Items from runs A and B were repeated in runs C and D (for a total number of 40 trials per verb group) in a different order. After each run, participants were given automated feedback on their percentage of accurate responses. E-Prime 2.0 software (http://www.pstnet.com/eprime.cfm) was used for stimulus presentation and recording of the responses.

2.3.1.5. Data analysis. fMRI analysis was the same as in Experiment 1 (Section 2.2.1.5) with the following modification: the first-level analysis included an additional regressor that was based on participants' trial-specific reaction times and obtained by creating a separate general linear model for each participant, with one condition type (collapsing across the six conditions) parametrically modulated by response time. A Monte Carlo simulation in AlphaSim yielded a cluster threshold for 27 contiguous voxels to correct for multiple comparisons at $\alpha = 0.05$ with a voxelwise threshold of $\alpha = 0.001$. Behavioral data analysis was the same as in Experiment 3 (Section 2.4.1.4, below).

2.3.2. Results

2.3.2.1. Behavioral results. The participants' accuracy on the lexical decision task was 97.8% on average (SD 4.0%, range 81.5–100.0%). Average reaction time was 805 ms (SD 84 ms, range 695–1023 ms). The three Bonferroni-corrected planned *t*-tests on reaction times revealed that verbs with a greater number of subcategorization options (*demand*-verbs) had significantly faster reaction times than verbs with a lower number of subcategorization options (*complete*-verbs) ($t(20) = 4.62$, $p < 0.001$); there were no significant effects of the number of thematic options (*sing*-verbs vs. *break*-verbs) ($t(20) = 1.48$, $p = 0.154$) or the number of valency frames (*sing*-verbs vs. *complete*-verbs) ($t(20) = 1.00$, $p = 0.330$) on reaction times. The three Bonferroni-corrected planned *t*-tests on accuracy revealed no effect of the number of subcategorization options (*complete*-verbs vs. *demand*-verbs) on accuracy ($t(20) = 1.70$, $p = 0.104$); verbs with a greater number of thematic options (*break*-verbs) showed higher accuracy than verbs with a lower number of thematic options (*sing*-verbs) ($t(20) = 3.24$, $p = 0.004$); verbs with a greater number of valency frames (*sing*-verbs) showed lower accuracy than verbs with a lower number of valency frames (*complete*-verbs) ($t(20) = 2.82$, $p = 0.004$).

2.3.2.2. Whole-brain fMRI analysis. Except for the effect of real over non-words, all significant differential activation clusters in Experiment 2 are presented in Table 4 and illustrated in Fig. 2.

2.3.2.2.1. Words versus non-words. The contrast of all verbs vs. non-words showed clusters of greater activation for verbs than non-words in a large bilateral network of frontal, temporal, parietal and occipital areas. Clusters of greater activation for non-words than words were located in pars opercularis of left inferior frontal gyrus, left precentral gyrus and right hippocampus.

2.3.2.2.2. Number of subcategorization options. The paired *t*-test analysis of *complete*-verbs vs. *demand*-verbs did not detect any clusters of increased activation associated with a greater number of subcategorization options. Clusters of increased activation associated with a lower number of subcategorization options were found in bilateral frontal and occipital lobes, as well as in the left parietal lobe.

2.3.2.2.3. Number of thematic options. The paired *t*-test analysis of *break*-verbs vs. *sing*-verbs did not detect any increased activation associated with a greater number of thematic options. Clusters of increased activation associated with a lower number of thematic options were found in the left posterior and mid-anterior middle temporal gyrus and insula.

2.3.2.2.4. Number of valency frames. The paired *t*-test analysis of *sing*-verbs vs. *complete*-verbs revealed increased activation associated with a greater number of valency frames in the left mid-anterior middle temporal gyrus. Increased activation associated with a lower number of valency frames was found in white matter underlying right middle temporal gyrus, as well as in the right-hemisphere caudate nucleus and cerebellum.

2.3.3. Summary

Experiment 2 used fMRI to investigate the neural correlates of three VAS characteristics in a single-word task. The analysis found areas of increased activation for more complex verbs for only one out of three investigated VAS characteristics: the number of valency frames (small cluster in left mid-anterior middle temporal gyrus), but not the number of subcategorization options or thematic options. Instead, the analysis found areas of increased activation for *less* complex verbs for all three VAS characteristics: the number of subcategorization options (in frontal and occipital lobe bilaterally, as well as left parietal lobe), the number of thematic options (in left mid-anterior and posterior middle temporal gyrus and insula) and the number of valency frames (small cluster in white matter underlying right middle temporal gyrus, as well as right caudate nucleus and cerebellum).

We interpret increased activation in association with VAS characteristics in both Experiments 1 and 2 as reflecting increased processing cost. However, less traditionally, it may also be interpreted as a consequence of more temporally focal and thus more easily detectable neural activity. To assess this possibility with a greater level of experimental control, a behavioral experiment was conducted outside the scanner to confirm whether conditions of increased activation also correspond to poorer behavioral performance and thus indeed reflect a greater processing load. Lexical decision behavioral data were collected in Experiment 2 but were again collected in the out-of-scanner experiment, since the latter

Table 4
AAL regions. MNI coordinates. cluster size and maximal *t*-values for activation clusters in Experiment 2 (voxelwise $p < 0.001$; cluster size (k) > 27). *L* – left, *R* – right, *bil.* – bilateral; *ant.* – anterior, *inf.* – inferior, *mid.* – middle, *post.* – posterior, *sup.* - superior. Mean (across-participant) contrast values relative to baseline were obtained with the MarsBaR toolbox in SPM (Brett et al., 2002).

L/R	Activation peak	Cluster extent	*x*	*y*	*z*	k	t-Max	*Mean contrast value*	
Greater number of subcategorization options (demand-verbs > complete-verbs)									
	None								
Lower number of subcategorization options (complete-verbs > demand-verbs)								*complete*	*demand*
L	Insula	Pars opercularis of inf. frontal gyrus	−30	26	10	91	5.72	3.45	1.57
L	Precentral gyrus	Pars opercularis of inf. frontal gyrus	−45	2	28	196	4.66	6.27	4.03
L	Inf. parietal lobule	Sup. parietal lobule	−27	−52	40	281	4.60	4.26	2.41
L	Inf. occipital gyrus	Inf. temporal gyrus, mid. temporal gyrus, fusiform gyrus, lingual gyrus	−54	−70	−11	170	4.53	4.09	1.97
L	Caudate nucleus	–	−9	17	4	121	4.40	1.69	−0.34
L	Mid. occipital gyrus	–	−42	−88	−5	44	4.23	5.70	4.01
bil.	L. sup. occipital gyrus	Bil. calcarine gyrus, R fusiform gyrus, R sup. occipital gyrus, R inf. occipital gyrus, bil. middle occipital gyrus, bil. cuneus, bil. lingual gyrus, R precuneus, R sup. parietal lobule, R inf. temporal gyrus, R cerebellum	−27	−64	19	2096	5.66	4.75	2.35
R	Putamen	Caudate nucleus	24	23	−5	107	5.00	2.28	0.50
R	Precentral gyrus	–	51	5	31	38	3.71	6.45	4.02
Greater number of thematic options (break-verbs > sing-verbs)									
	None								
Lower number of thematic options (sing-verbs > break-verbs)								*sing*	*break*
L	Mid. temporal gyrus	–	−57	−4	−23	47	5.10	0.34	−1.32
L	Insula	–	−24	14	−20	42	4.45	1.20	−0.77
L	Mid. temporal gyrus	–	−54	−46	−8	29	3.73	2.51	0.32
Greater number of valency frames (sing-verbs > complete-verbs)								*sing*	*complete*
L	Mid. temporal gyrus	–	−57	−1	−29	37	4.66	0.46	−1.14
Lower number of valency frames (complete-verbs > sing-verbs)								*complete*	*sing*
R	White matter underlying middle temporal gyrus		45	−46	−2	32	4.77	1.61	0.49
R	Caudate nucleus	–	21	23	−5	39	4.73	1.76	0.50
R	Cerebellum	–	6	−67	−17	34	4.13	4.91	3.07

provided a more comfortable environment for participants, allowed us to use a constant inter-stimulus interval and to collect sentence judgment and lexical decision data from the same participants, which should all contribute to greater reliability of behavioral results.

2.4. Experiment 3: Behavioral effects of VAS processing

2.4.1. Method

2.4.1.1. Participants. Twenty college-age volunteers participated in the study (14 females; mean age 22.4, range 19–30). All participants were right-handed native speakers of English with normal or corrected-to-normal vision and no history of neurological or speech-language disorders. None of the participants had participated in Experiments 1 or 2, which included the same stimuli as Experiment 3. All participants gave informed consent prior to the experiment, in accordance with the Helsinki declaration.

2.4.1.2. Task. The lexical decision task was identical to the task in Experiment 2, except that the inter-stimulus interval was fixed at 1.5 s. The sentence task was identical to the task in Experiment 1, except that the inter-stimulus interval was fixed at 2.0 s and participants had to make a button-press response to all stimuli (well-formed and non-well-formed sentences).

2.4.1.3. Design and stimuli. The study design is described in Section 2.1. Lexical decision stimuli were identical to those in Experiment 2 with the following exceptions: the word-nonword ratio was 1:2 and each stimulus was only repeated once. The sentence-level stimuli were identical to those in Experiment 1, with the exception of 14 sentences (i.e., 7 verbs) that were changed in order to improve imageability matching.

2.4.1.4. Procedures. Participants were seated in front of a laptop in a quiet room. After instructions and practice, participants first completed the lexical decision task and then the sentence task, so that the presentation of verbs in isolation in the lexical decision task could not be affected by any memory traces of sentences. Order of individual stimulus presentation was randomized for each participant. E-Prime 2.0 software (http://www.pstnet.com/eprime.cfm) was used for stimulus presentation and recording of responses.

2.4.2. Data analysis

Reaction times and accuracy were analyzed separately for the lexical decision task and the sentence task. Only correct responses were included in the analysis of reaction times. Accuracy values were log-transformed prior to statistical tests (Bartlett, 1947; Hoyle, 1973). Three a priori planned paired *t*-tests were performed for the contrasts described in Section 2.1. For each outcome mea-

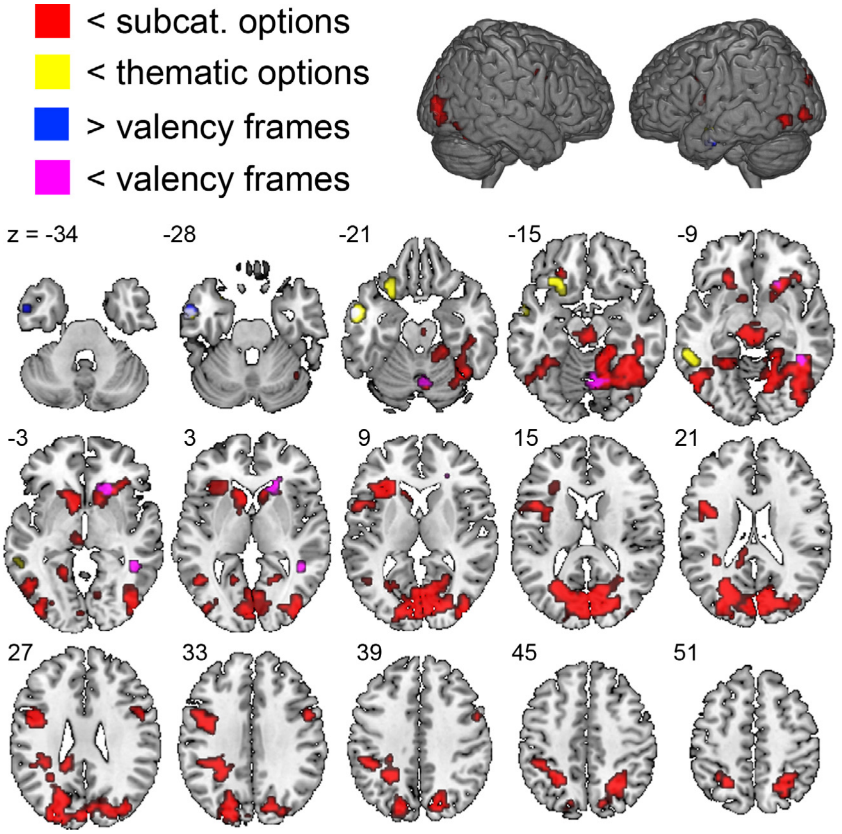

Fig. 2. Differential activation clusters in Experiment 2 (voxelwise $p < 0.001$; cluster size $(k) > 17$). Red = Lower number of subcategorization options (*complete*-verbs > *demand*-verbs); Yellow = Lower number of thematic options (*sing*-verbs > *break*-verbs); Blue = Greater number of valency frames (*sing*-verbs > *complete*-verbs); Violet: Lower number of valency frames (*complete*-verbs > *sing*-verbs).

sure, Bonferroni correction for multiple comparisons was applied, resulting in $\alpha = 0.017$ for an overall significance threshold of $\alpha = 0.05$. Analysis was performed in SPSS 22.

2.4.3. Results

2.4.3.1. Lexical decision task. In the lexical decision task, the average accuracy was 96.5% (SD 2.9%, range 88.8–100.0%) and the average reaction time was 652 ms (SD 58 ms, range 662–797 ms).

The three Bonferroni-corrected planned paired *t*-tests on reaction times revealed that verbs with a greater number of subcategorization options (*demand*-verbs) had faster reaction times than verbs with a lower number of subcategorization options (*complete*-verbs) ($t(19) = 3.52$, $p = 0.002$); verbs with a greater number of thematic options (*break*-verbs) had faster reaction times than verbs with a lower number of thematic options (*sing*-verbs) ($t(19) = 2.82$, $p = 0.011$); no difference was found between verbs with a greater number of valency frames (*sing*-verbs) and verbs with a lower number of valency frames (*complete*-verbs) ($t(19) = 0.41$, $p = 0.68$) (see Fig. 3).

The three Bonferroni-corrected planned paired *t*-tests on log-transformed accuracy revealed that there was no difference in accuracy between verbs with a greater number of subcategorization options (*demand*-verbs) and verbs with a lower number of subcategorization options (*complete*-verbs) ($t(19) = -0.78$, $p = 0.446$), nor between verbs with a greater number of thematic options (*break*-verbs) and verbs with a lower number of thematic options (*sing*-verbs) ($t(19) = 2.08$, $p = 0.052$), nor between verbs with a greater number of valency frames (*sing*-verbs) and verbs with a lower number of valency frames (*complete*-verbs) ($t(19) = 0.97$, $p = 0.343$).

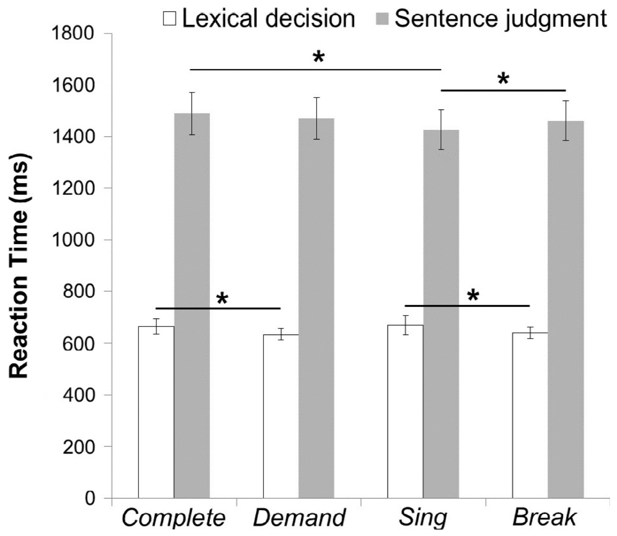

Fig. 3. Mean reaction times per experimental condition in Experiment 3. Error bars represent standard errors of the mean. Asterisks indicate significant pairwise comparisons ($p < 0.05$).

2.4.3.2. Sentence task. In the sentence task, the average accuracy was 92.0% (SD 3.3%, range 85.0–96.3%) and the average reaction time was 1489 ms (SD 178 ms, range 1067–1786 ms).

The three Bonferroni-corrected planned paired *t*-tests on reaction times revealed there was no difference in reaction times between verbs with a greater number of subcategorization options (*demand*-verbs) and verbs with a lower number of subcategorization options (*complete*-verbs) ($t(19) = 1.12$, $p = 0.277$); verbs with a greater number of thematic options (*break*-verbs) showed slower reaction times than verbs with a lower number of thematic options (*sing*-verbs) ($t(19) = 3.30$, $p = 0.004$); verbs with a greater number of valency frames (*sing*-verbs) showed faster reaction times than verbs with a lower number of valency frames (*complete*-verbs) ($t(19) = 3.57$, $p = 0.002$) (see Fig. 3).

The three Bonferroni-corrected planned paired *t*-tests on accuracy revealed that there was no difference in accuracy between verbs with a greater number of subcategorization options (*demand*-verbs) and verbs with a lower number of subcategorization options (*complete*-verbs) ($t(19) = 0.16$, $p = 0.878$), nor between verbs with a greater number of thematic options (*break*-verbs) and verbs with a lower number of thematic options (*sing*-verbs) ($t(19) = 1.76$, $p = 0.094$), nor between verbs with a greater number of valency frames (*sing*-verbs) and verbs with a lower number of valency frames (*complete*-verbs) ($t(19) = 0.41$, $p = 0.689$).

2.4.4. Summary

Experiment 3 investigated behavioral effects of three VAS characteristics in a single-word and a sentence-level task. A greater number of subcategorization options did not affect sentence judgment but increased processing speed in lexical decision. A greater number of thematic options decreased processing speed in sentence judgment but increased processing speed in lexical decision. A greater number of valency frames increased processing speed in sentence judgment but had no effect in lexical decision. Neither of the three VAS characteristics affected accuracy of lexical decision or sentence judgment.

3. Overall discussion

We conducted a series of fMRI and behavioral experiments to investigate how VAS characteristics other than the well-studied parameter of valency (the number of arguments) modulate the behavioral processing cost and neural correlates of verb processing. The three investigated characteristics were the number of subcategorization options, the number of thematic options and the number of valency frames. Their effects were tested under two different processing conditions that varied in both the context of verb use and in task demands: single-word context with a lexical decision task and sentence context with a well-formedness judgement task. Results of all three experiments are summarized in Table 5. The number of subcategorization and thematic options showed a similar task-dependent pattern. This suggests that linguistic complexity may have a facilitatory or detrimental effect depending on the task (Section 3.1). The number of valency frames did not appear to have a robust effect.

3.1. Task-dependent effects of VAS characteristics

The most striking result was that effects of all three investigated VAS characteristics were modulated by processing conditions (task). More linguistically complex VAS representations did not always increase the processing load. Instead, whether greater VAS complexity increased or reduced the processing cost depended on the processing conditions (context and task, which were not teased apart in the present study). This task-dependent pattern was observed for the number of subcategorization options and the number of thematic options (although not for the number of valency frames, see discussion below in Section 3.2). For both the number of subcategorization and thematic options, greater VAS complexity played a facilitatory role in a single-word lexical decision task (as reflected by better behavioral performance and less extensive neural recruitment) and a negative role in a sentence-level well-formedness judgement task (as reflected by poorer behavioral performance and more extensive neural recruitment). Coupling of increased neural activation with poorer behavioral performance is important because it strongly suggests that the measured BOLD response reflects increased cognitive processing load, rather than more temporally focal and thus more easily detectable brain activity.

Specifically, in the sentence task, a *greater* number of subcategorization options was associated with increased activation in left superior frontal gyrus and temporo-parietal junction extending to posterior middle temporal gyrus. In the lexical decision task, a *lower* number of subcategorization options was associated with increased activation in the frontal lobe bilaterally, occipital lobe bilaterally and in the left parietal lobe, as well as with decreased processing speed (replicated across Experiments 2 and 3). The pattern was similar for the number of thematic options. In the sentence task, a *greater* number of thematic options was associated with small clusters of activation in the left cingulum and in white matter underlying the left inferior frontal gyrus, as well as with slower processing speed. In the lexical decision task, a *lower* number of thematic options was associated with increased activation in the left mid-anterior and posterior middle temporal gyrus and insula, as well as with slower processing speed (Experiment 3) and reduced accuracy (Experiment 2).

To account for this pattern, we suggest a facilitation-through-complexity account of single-word-level results. A greater number of VAS options may in fact "strengthen" verb representations and make them more "robust" or provide them with additional lexical

Table 5
Summary of results of three experiments.

	Sentence level (Experiments 1, 3)		Single-word level (Experiments 2, 3)	
	Areas of increased neural activation	Behavioral effects	Areas of increased neural activation	Behavioral effects
Number of subcategorization options	Greater number: left superior frontal gyrus, temporo-parietal junction, posterior middle temporal gyrus Lower number: n/s	n/s	Greater number: n/s Lower number: frontal and occipital lobe bilaterally, left parietal lobe	Greater number: faster processing
Number of thematic options	Greater number: left cingulum, white matter underlying left inferior frontal gyrus Lower number: right angular gyrus	Greater number: slower processing	Greater number: n/s Lower number: left mid-anterior and posterior middle temporal gyrus, insula	Greater number: faster processing
Number of valencies	Greater number: n/s Lower number: left superior frontal gyrus	Greater number: faster processing	Greater number: middle temporal gyrus Lower number: small clusters in white matter underlying right middle temporal gyrus, right caudate nucleus and cerebellum	n/s

n/s = no significant activation/effect.

access routes by building more connections in the mental lexicon (similar to semantic neighborhood density effects, e.g., Buchanan, Westbury, & Burgess, 2001). In other words, additional VAS options provide verbs with richer semantic features and more semantic connections (Rodriguez-Ferreiro et al., 2014). This may facilitate lexical access under processing conditions such as single-word processing, when not all of the verb's associated information needs to be fully activated. In other words, lexical search is aided by superficial/transient activation of semantic associates of the verb, including its arguments, without full/exhaustive activation of grammatical information about VAS options. On the other hand, representations of verbs with a lower number of VAS options have fewer connections in the mental lexicon and thus are more difficult to access.

In contrast, sentence processing requires not only access to VAS information but also selection and integration of appropriate components of this information. Under these conditions, sentence-level demands for access and/or integration of VAS options neutralize or override the benefits of more robust lexical representations of verbs with a greater number of VAS options. Firstly, it may be more demanding to exhaustively access a more numerous set of VAS options. Secondly, with an increase in the number of VAS options, it may be more demanding to resolve their competition (inhibit irrelevant options and select appropriate ones) and integrate them into sentence context. Moreover, if the verb did not appear in a sentence with its "preferred" (most frequent) VAS option, this may require syntactic re-analysis, or adjustment of the initial prediction, also increasing the processing cost. Such re-analysis is not involved in single-word processing. In more general terms, task-dependent effects arise because the goal of processing modulates which subprocesses are drawn on, which linguistic features need to be accessed, and how deeply or shallowly. This shift of focus in processing may be adopted strategically (consciously) or occur in an automated way (see Fischer-Baum, Dickson, & Federmeier, 2014).

In single-word processing, increased activation for verbs with a lower number of subcategorization and thematic options likely reflects lexical access demands in both cases. But in sentence processing, the nature of additional load may differ between subcategorization and thematic options. A greater number of subcategorization options in sentence processing was associated with activation in left posterior temporal and temporo-parietal areas, reminiscent of areas activated for greater valency in previous research (Den Ouden et al., 2009; Thompson et al., 2007). These areas are likely associated with semantic storage/retrieval, as suggested by both general neurobiological models of semantic processing (Binder et al., 2009) and more specific neurobiological models of VAS processing (Thompson & Meltzer-Asscher, 2014). The angular gyrus is located at the temporo-parieto-occipital junction and is often implicated in high-level semantic processing tasks (e.g., Seghier, 2013). Binder et al. (2009) suggest that the angular gyrus is a "hub" area at the top of a processing hierarchy underlying concept retrieval. The posterior middle temporal area possibly subserves sound-to-meaning mapping, as a "lexical interface" (Hickok & Poeppel, 2004, 2007). We believe that activation of both these regions reflects greater demands on fully retrieving the verb's subcategorization options, possibly in prediction/anticipation of the verb's complement (Kamide, 2008). Possibly, the role of the angular gyrus is to guide retrieval, whereas posterior middle temporal cortex is involved in lexico-semantic storage. However, other interpretations are possible. For example, Bornkessel-Schlesewsky and Schlesewsky (2013) highlight the role of posterior perisylvian structures in syntactic processing, suggesting that the angular gyrus and posterior temporal cortex are involved in building the sentence structure (establishing "sentence-internal relations") rather than in semantic storage/retrieval alone.

By contrast, a greater number of thematic options in the sentence-level task was associated with activation in white matter underlying pars orbitalis and opercularis of the left inferior frontal gyrus. This area likely overlaps with fiber tracts that feed these regions, often implicated in structure building and integration (e.g., Friederici, 2011; Meyer et al., 2012; Thompson & Meltzer-Asscher, 2014). More specifically, Friederici (2009) argues that two pathways from left IFG make different contributions to sentence processing: a dorsal pathway to the posterior temporal cortex supports parsing of hierarchical structure in syntactically complex sentences, and a ventral pathway to the anterior temporal cortex supports combination of adjacent sentence elements. The present study did not include connectivity analyses to establish which of these pathways is more involved in processing thematic options; this can be a subject of further research. Still, activation found in white matter adjacent to left IFG suggests that the processing of sentences containing verbs with a greater number of thematic options poses greater demands on integrating VAS options into sentence context. Alternatively, activation adjacent to left IFG may reflect selection of the appropriate VAS option out of multiple possibilities (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Both the number of subcategorization options and the number of thematic options, then, pose higher processing demands in sentence processing, but for different reasons.

An exception to the pattern of facilitatory effects of lower VAS complexity in single-word processing was greater activation in the right angular gyrus for verbs with a lower number of thematic frames (*sing*-verbs, or verbs undergoing unspecified object alternation) in the sentence task. One possibility is that the "pragmatic focus" of these verbs is on the activity itself rather than on the object, which is assumed to be prototypical when omitted (Rappaport Hovav & Levin, 1998; Rice, 1988). Thus, transitive use of these verbs likely requires a shift of focus from the action to the object, increasing the processing load. This is consistent with localization of increased activation in the right hemisphere. Right lateralization may reflect activation of more "distantly related semantic information ... that may be needed to re-direct comprehension if an initial, dominant interpretation needs to be abandoned in favor of some other reading" (Brownell & Martino, 1998). However, this was not an expected result and any post hoc interpretation remains speculative.

The facilitatory effect of greater VAS complexity in single-word processing (where, unlike in sentence processing, there is no need to predict the upcoming sentence material) is inconsistent with most previous literature, which has largely found a greater processing cost when VAS complexity is greater. Still, facilitatory effects of greater VAS complexity have been reported before. For example, Thompson et al. (2007) report faster processing of verbs with a greater valency in lexical decision. It is noteworthy that most previous VAS research has focused on valency, whereas literature on other VAS characteristics is more sparse and lacks consistency, possibly due to differences in stimuli and, importantly, experimental design. For example, Meltzer-Asscher et al. (2015) investigated the effects of the number of valency frames by comparing alternating (one/two-argument) verbs to both one-argument and two-argument non-alternating verbs, whereas in the present research the latter group was restricted to two-argument non-alternating verbs. Shetreet et al. (2007) employed a parametric design to analyze the effect of the number of subcategorization options, whereas the present study analyzed the effect in a binary comparison.

To resolve the above inconsistencies, further research can systematically investigate VAS effects across tasks and linguistic contexts. Tasks should include both single-word level processing (on a continuum from more "superficial" tasks such as lexical decision to more semantically involved tasks) and sentence-level processing. Linguistic contexts should also vary: e.g., the effect of the number of thematic options can be investigated in intransitive contexts, transitive contexts and without further context, similar to the approach taken by Shetreet et al. (2010). Of course, this research goal is complicated by the difficulty of matching the demands of different experimental tasks, which is not always straightforward. For example, in the present study, we opted for different overt response requirements and ratio of filler items in the two tasks because, as outlined in Section 2.3.1.2, it seemed that formal matching of the two tasks on these parameters would actually introduce rather than eliminate confounding by processing strategies. However, we admit that a different choice could be argued for, putting greater emphasis on matching the tasks formally, and it would be of interest to see how this may affect the results.

Despite the difficulty of carefully matching experimental tasks, task-related effects have received increasing attention in various areas of neurolinguistic research (e.g., syntactic comprehension in aphasia: Caplan, Michaud, & Hufford, 2015) and warrant attention in verb argument structure research as well. Our results suggest that there are several levels of verb processing, with different degrees of access to VAS features depending both on the context of verb use and on task demands. At the single-word level, if the task poses only lexical access demands and does not directly pertain to grammar, verbs do not have to be actively processed and there is no need to access their VAS options, actively. Still, VAS characteristics have an impact: more linguistically complex verbs may benefit from multiple lexical access routes that have been established in the mental lexicon. The second level is verb processing in sentence comprehension. For the purposes of efficient processing (e.g., for prediction of upcoming sentence material), potential VAS options of the verb are retrieved from the mental lexicon, which leads to greater storage/retrieval demands for more complex verbs. In sentence processing, therefore, the direction of VAS effects is the opposite to what is observed in lexical processing. One may hypothesize that there is also a third level of verb processing that was beyond the scope of the present research: verb processing in active sentence-level tasks such as sentence *production*. In production, the *context* of verb use remains the same as in sentence comprehension but processing is modulated by *task* demands. At this level, VAS options would need not only to be retrieved, as in sentence comprehension, but also to be actively manipulated for the purposes of structure-building and integration in a sentence.

3.2. Semantic account of VAS effects

As discussed above, increased activation for verbs with a greater number of subcategorization/thematic options was observed in the sentence-level task, which requires deep semantic processing, but not in the lexical decision task that only requires superficial access to lexical entries. This suggests that an additional load imposed by verbs with a greater number of subcategorization/thematic options is largely mediated by their semantic properties, rather than by automated exhaustive access to purely grammatical VAS information (see a similar semantic-based analysis of complement coercion in Piñango & Deo, 2015). In terms of lexicalist versus constructivist accounts of VAS effects, this idea is most consistent with constructivism, which argues that there is no need for a separate VAS module in lexical representations of verbs because VAS properties can be induced from verb semantics. The same semantic account seems valid for the robust effects of the number of arguments found in previous literature (not investigated here). The number of arguments reflects the number of participants of the event denoted by the verb and is therefore a highly semantically meaningful characteristic. Thus, its effects may be due to semantic/conceptual processing of participant roles, rather than to processing of separate VAS modules containing grammatical information on valency. Along the same lines, Shetreet et al. (2007) point out that processing the number of arguments may rely on general cognitive resources, rather than "specifically linguistic" networks.

The semantic account of VAS effects finds further support in a different pattern of results for the number of valency frames than for the number of subcategorization/thematic options in our experiments. In the sentence-level task, a greater number of valency frames had a facilitatory effect at the behavioral level and showed no additional neural recruitment, whereas a lower number of valency frames was associated with increased activation in the left superior frontal gyrus, as well as with slower processing speed. In the single-word task, a greater number of valency frames was associated with increased activation in left mid-anterior middle temporal gyrus and with reduced accuracy (in Experiment 2 only; not replicated in Experiment 3), whereas a lower number of valency frames was associated with increased activation of white matter underlying right middle temporal gyrus and in right caudate nucleus and cerebellum. These results do not appear very robust: all neural activation clusters had very small volume and behavioral results were not replicated between Experiments 2 and 3. In previous literature, effects of the number of valency frames are not robust either. Many studies failed to find any significant effects (Ahrens & Swinney, 1995; Meltzer-Asscher et al., 2015) or demonstrated effects in opposite directions (Shetreet et al., 2007, 2010). These findings suggest that valency frames are not exhaustively activated in verb processing. Instead, language users may access a single (most prominent) valency frame and then (exhaustively) all subcategorization and thematic options possible within that frame.

A possible reason why the number of valency frames yielded different results than other VAS characteristics is that it is likely the most "syntactic" out of the three VAS characteristics investigated in our series of experiments. In other words, the other two investigated VAS characteristics are more closely associated with semantic properties of verbs. For instance, verbs with a greater number of subcategorization options have a common semantic property: they allow complementation by a proposition (e.g., Rudanko, 1996). The number of thematic options also has semantic correlates: verbs with a greater number of thematic options typically describe a change of state (e.g., Wright, 2002) and verbs with a lower number of thematic options (undergoing unspecified object alternation) refer to activities and have a prototypical object (Rappaport Hovav & Levin, 1998; Rice, 1988). Even though stimulus groups were matched for imageability as a crucial semantic parameter, inherent differences in semantics still remain. There seem to be no such salient semantic differences between verbs with a greater versus lower number of valency frames. So, strong effects were found primarily for VAS characteristics intertwined with semantic properties. Thus, we may again speculate that the neural effects of the number of subcategorization options and thematic options are actually mediated by accessing *semantic* information, rather than a separate grammatical component in a verb's lexical entry that contains VAS information. If information on the verb's valency frames is not of semantic nature and needs to be specified in the lexicon, this in itself runs counter to a strong constructivist account of VAS access that relies on semantic (rather than lexico-syntactic) grounding of all VAS characteristics. Nevertheless, robust processing effects appear to be task-dependent and mediated by semantics, which is more in line with constructivist (semantic) rather than lexicalist accounts of VAS processing.

Another finding consistent with the semantic account is that VAS effects in people with non-fluent/agrammatic aphasia are similar to those found in healthy speakers. For example, both groups demonstrate a detrimental effect of greater valency (Collina, Marangolo, & Tabossi, 2001; Kim & Thompson, 2000; Thompson, 2003; Thompson, Lange, Schneider, & Shapiro, 1997). So far, researchers have mainly taken this evidence to argue that VAS *representations* are intact in aphasia, whereas VAS *processing* is impaired (e.g., Kielar, Meltzer-Asscher, & Thompson, 2012). The present research, however, suggests that VAS effects in non-fluent aphasia may actually be due to near-normal *semantic* processing in these patients. In line with this, individuals with Wernicke's aphasia do *not* always demonstrate the same VAS effects as healthy individuals. For example, they do not show online sensitivity to thematic properties of verbs (Russo, Peach, & Shapiro, 1998; Shapiro, Gordon, Hack, & Killackey, 1993; although see Edwards and Bastiaanse (1998) for normal-like distribution of VAS characteristics in spontaneous speech in fluent aphasia). Since syntactic representations are presumably intact in Wernicke's aphasia, atypical VAS effects in this population provide additional support for the idea that VAS effects are mediated by semantics rather than by a separate grammatical component of verb representations.[2]

Further research can test the semantic account of VAS effects in dedicated experiments. A related research direction is to investigate the effects of *possible* vs. *statistically preferred* VAS options, which were not specifically controlled in our experiments. Such research can test whether the processing cost of verbs with certain VAS options is modulated by the relative usage frequency of these options, rather than by their mere possibility (similar to the approach taken in research on verb transitivity bias; e.g., DeDe, 2013).

3.3. Implications for aphasia research and treatment

Since VAS effects are found in language processing in healthy individuals (regardless of their possibly semantic nature), it seems beneficial to take VAS features into account when selecting verb stimuli for complexity-based aphasia treatments. So far, such complexity-based treatments have mainly characterized verbs in terms of their valency (Bazzini et al., 2012; Thompson et al., 2013), sequencing stimuli from verbs with fewer arguments to verbs with more arguments (Rochon et al., 2005) or vice versa (Thompson et al., 2013). The present research indicates that the number of subcategorization options and the number of thematic options also affect the cost of verb processing. Thus, sequencing of stimuli in complexity-based treatments may be improved by incorporating these two characteristics. By contrast, the number of valency frames shows very inconsistent effects at the behavioral and neural level. Thus, manipulation of this verb characteristic seems less relevant in language treatments based on VAS complexity. Another clinical implication for behavioral aphasia treatments is that since VAS effects appear to have a semantic nature, activities aiming to improve VAS processing may be most beneficial if they focus on the meanings of verbs and their arguments (as in Verb Network Strengthening Treatment, Edmonds, Nadeau, & Kiran, 2009), rather than on grammatical transformations or on automated access to verb forms.

4. Conclusions

As reflected by behavioral performance and neural recruitment patterns, the number of subcategorization options and thematic options affect the verb processing cost. The direction of these effects depends on processing conditions: increased VAS complexity is associated with a greater load in sentence processing but, paradoxically, facilitates lexical access to single words, possibly by providing more lexico-semantic associations and access routes (facilitation through complexity). In a sentence processing task, which necessarily draws on VAS knowledge, a greater number of subcategorization options was associated with increased activation in left superior frontal gyrus and the temporo-parietal junction extending to posterior middle temporal gyrus, whereas a greater number of thematic options was associated with activation in white matter underlying the left inferior frontal gyrus. The number of valency frames, as a less semantically meaningful VAS characteristic, only shows equivocal effects on verb processing, suggesting that VAS effects are mediated by semantic processing rather than a dedicated lexico-syntactic VAS module in verb representations.

Acknowledgements

This research was supported by a Support to Promote Advancement of Research and Creativity (SPARC) Graduate Research Grant from the University of South Carolina, to SM. The article was prepared within the framework of the Basic Research Program at the National Research University Higher School of Economics (HSE) and supported within the framework of a subsidy by the Russian Academic Excellence Project '5-100'.

Appendix A

Full list of verbs and the corresponding sentence stimuli, with justification of inclusion of verbs into experimental groups (see Tables A.1–A.4).

Table A.1
Full list of *complete*-verbs.

#	Verb	Experimental sentence 1	Experimental sentence 2
1	abandon	The army abandoned the city	The collie abandoned her puppy
2	complete	The user completed the survey	The students completed the exam
3	consume	The society consumed the resources	The engine consumed the fuel
4	create	The artist created a masterpiece	The law created the problem
5	destroy	The hurricane destroyed the roofs	The storms destroyed the houses
6	encounter	The expedition encountered the tribes	The police encountered the fight
7	fulfill	The governor fulfilled the promise	The teenager fulfilled her dreams
8	own	The farmer owned the terrain	The grandfather owned the apartment
9	produce	The factory produced the device	The band produced the album
10	accomplish	The team accomplished the mission	The teacher accomplished the goal
11	contact	The client contacted the clerk	The principal contacted the parents
12	invent	The engineer invented the machine	The insurer invented the scheme
13	acquire	The apprentice acquired the skills	The millionaire acquired the properties
14	conquer	The tribes conquered the land	The army conquered the nation
15	ruin	The tornado ruined the mansion	The heat ruined the salad
16	capture	The hunter captured the tiger	The cat captured the mouse
17	wreck	The captain wrecked the ship	The rocks wrecked the ship
18	discard	The clerk discarded the trash	The baby discarded his blanket
19	generate	The factory generated the power	The assembly generated much dissent
20	whisk	The cook whisked the eggs	The wife whisked the mixture

---

[2] It may seem contradictory to the semantic account that Whitworth, Webster, and Howard (2015) report the case of a patient who does not have any lexical-semantic deficits in single-word verb and noun production but cannot produce correct VAS structures. However, intact word production indicates good retrieval of phonological forms, whereas the ability to use semantic (rather than necessarily grammatical) information to guide sentence construction may still be impaired. Thus, this interesting clinical case still does not point to a need for separate VAS modules in verb representations.

Table A.2

Full list of *break*-verbs. To justify inclusion into this group, examples of transitive and intransitive use (with different thematic roles of the sentence subject) are provided in addition to experimental stimuli.

#	Verb	Experimental sentence 1	Experimental sentence 2	Example of intransitive use
1	open	The janitor opened the door	The woman opened the box	The door opened
2	break	The thief broke a lock	The worker broke the glass	The handle broke
3	operate	The worker operated the crane	The driver operated the lift	The service operated on weekdays
4	accelerate	The pilot accelerated the helicopter	The group accelerated their departure	The vehicle accelerated
5	spin	The toddler spun the top	The athlete spun the ball	The dancer spun gracefully
6	broaden	The workers broadened the street	The students broadened their knowledge	My horizons broadened
7	dry	The model dried her hair	The swimmer dried the towel	The laundry dried in the sun
8	gather	The mayor gathered the citizens	The organizers gathered the protesters	The staff gathered for a meeting
9	unite	The campaign united the politicians	The leader united the factions	The state united after the war
10	assemble	The king assembled his subjects	The principal assembled the students	The crowd assembled in the hall
11	close	The owner closed the store	The worker closed the valve	The door closed
12	accumulate	The carpet accumulated the dirt	The collector accumulated the stamps	Money accumulated in her account
13	worsen	The rain worsened the situation	The policies worsened the crisis	The patient's condition worsened
14	collapse	The explosion collapsed the warehouse	The blast collapsed the building	The barn collapsed
15	burn	The writer burned the manuscript	The housewife burnt the pan	The candle burnt in the dark
16	dissolve	The chemist dissolved the compound	The water dissolved the sugar	The chemical dissolved fast
17	brighten	The sun brightened the sky	The lamp brightened the hall	The sky brightened
18	drop	The cashier dropped the receipt	The mover dropped the box	The temperature dropped
19	grow	The gardener grew the vegetables	The farmer grew the cotton	The child grew fast
20	collect	The scientist collected the samples	The researcher collected the insects	The public collected in the hall

Table A.3

Full list of *sing*-verbs. To justify inclusion into this group, examples of transitive and intransitive use (with the same thematic roles of the sentence subject) are provided in addition to experimental stimuli.

#	Verb	Experimental sentence 1	Experimental sentence 2	Example of intransitive use
1	draw	The architect drew the temple	The artist drew a helicopter	The girl drew in her free time
2	visit	The student visited the gallery	The family visited the coast	Her parents visited last week
3	knit	The grandmother knitted the pattern	The lady knitted the sweater	The grandmother knitted in her free time
4	perform	The musician performed the songs	The actress performed a monologue	Her sister performed on stage
5	sing	The child sang a carol	The choir sang the chorus	Mary sang well
6	divorce	The journalist divorced his wife	The actress divorced her husband	The doctor divorced two years ago
7	marry	The teacher married her colleague	The director married his girlfriend	John married young
8	miss	The player missed the target	The plane missed the runway	The sniper missed pathetically
9	obey	The suspect obeyed the orders	The toddler obeyed the command	The soldier silently obeyed
10	clean	The maid cleaned the room	The janitor cleaned the classrooms	Adam cleaned all Sunday
11	achieve	The group achieved the result	The writer achieved great success	The girl achieved well in school
12	recite	The teacher recited the poem	The author recited the story	The child recited loudly
13	embroider	The princess embroidered the pillow	The cousin embroidered the patch	Anna embroidered in her spare time
14	adopt	The applicants adopted a toddler	The family adopted a baby	The couple adopted in 2002
15	hum	The runner hummed the melody	The baby hummed a tune	The driver hummed softly
16	rehearse	The actors rehearsed the play	The cast rehearsed their lines	The cast rehearsed for two hours
17	follow	The dinner followed the lecture	The dogs followed the trail	The car followed closely behind me
18	entertain	The game entertained the guests	The comedy entertained the audience	Sarah was not good at entertaining
19	exaggerate	The report exaggerated the details	The media exaggerated the risks	My mother exaggerated in her letter
20	advertise	The flyer advertised the performance	The school advertised the openings	The company advertised on TV

Table A.4

Full list of *demand*-verbs. To justify inclusion into this group, examples of use complemented by a noun phrase and by a phrase of a different category (e. g., subordinate clause) are provided in addition to experimental stimuli.

#	Verb	Experimental sentence 1	Experimental sentence 2	Example of intransitive use
1	hate	The swimmer hated the referee	The sister hated the soup	The girl hated that her parents were away
2	demand	The buyer demanded a refund	The landlord demanded the keys	The attorney demanded that they listen to him
3	reveal	The records revealed the secrets	The test revealed the flaws	The test revealed that the disease was caused by a virus
4	promise	The company controlled the market	The parents controlled the phone	The president promised that there will be new tax cuts
5	arrange	The mayor promised a change	The union promised a strike	The businessman arranged that they meet
6	declare	The florist arranged the flowers	The planners arranged the wedding	The convict declared that he had been unaware of the penalty
7	neglect	The president declared a partnership	The queen declared her will	The worker neglected to perform her duties
8	announce	The boss neglected the proposals	The babysitter neglected the kids	The model announced that they were divorcing
9	advise	The artist recalled the colleague	The journalist recalled the fight	The doctor advised that the patient should take a new medication
10	witness	The pharmacist recommended a drug	The speaker recommended a textbook	The neighbor witnessed in court
11	challenge	The couple announced their engagement	The radio announced the decision	Mr. Jones challenged that he could remain the executive director
12	predict	The teacher suspected the truth	The police suspected the brother	The old man predicted that this would be the end
13	desire	The mentor advised a revision	The judge advised the prisoner	The public desired that everything should change
14	adore	The neighbor witnessed the attack	The couple witnessed the sunrise	Mary adored when he called
15	conceal	The experiment challenged the theories	The tasks challenged the class	The employee concealed that he had been accused of the crime
16	discover	The prophet predicted a war	The forecast predicted the weather	The host discovered that the guests had left
17	discuss	The book prophesied a change	The writer prophesied the end	The panel discussed how the law should be interpreted
18	accept	The society desired a reform	The client desired a replacement	The brother accepted that it was reasonable
19	rule	The aunt adored the cats	The sister adored the skirt	The king ruled that it should be considered illegal
20	seek	The couple planned a vacation	The coach planned the trip	The player sought to win

References

Assadollahi, R., Meinzer, M., Flaisch, T., Obleser, J., & Rockstroh, B. (2009). The representation of the verb's argument structure as disclosed by fMRI. *BMC Neuroscience, 10*(1), 3.

Baayen, R., Piepenbrock, R., & Gulikers, L. (1995). *CELEX2 LDC96L14*. Philadelphia: Linguistic Data Consortium. Web Download.

Bartlett, M. S. (1947). The use of transformations. *Biometrics, 3*(1), 39–52.

Bazzini, A., Zonca, G., Craca, A., Cafforio, E., Cellamare, F., Guarnaschelli, C., ... Luzzatti, C. (2012). Rehabilitation of argument structure deficits in aphasia. *Aphasiology, 26*(12), 1440–1460.

Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex, 19*(12), 2767–2796.

Boland, J. E., & Blodgett, A. (2006). Argument status and PP-attachment. *Journal of Psycholinguistic Research, 35*, 385–403.

Bookheimer, S. (2002). Functional MRI of language: New approaches to understanding the cortical organization of semantic processing. *Annual Review of Neuroscience, 25*, 151–188.

Bornkessel-Schlesewsky, I., & Schlesewsky, M. (2013). Reconciling time, space and function: A new dorsal-ventral stream model of sentence comprehension. *Brain and Language, 125*, 60–76.

Brett, M., Anton, J. L., Valabregue, R., & Poline, J. B. (2002). Region of interest analysis using an SPM toolbox. *NeuroImage, 16*(2), 497.

Brownell, H., & Martino, G. (1998). Deficits in inference and social cognition: The effects of right hemisphere brain damage on discourse. In M. Beeman & C. Chiarello (Eds.), *Right hemisphere language comprehension: Perspectives from cognitive neuroscience* (pp. 309–328). Mahwah, NJ: Lawrence Erlbaum Associates.

Buchanan, L., Westbury, C., & Burgess, C. (2001). Characterizing semantic space: Neighborhood effects in word recognition. *Psychonomic Bulletin & Review, 8*, 531–544.

Caplan, D., Michaud, J., & Hufford, R. (2015). Mechanisms underlying syntactic comprehension deficits in vascular aphasia: New evidence from self-paced listening. *Cognitive Neuropsychology, 32*(5), 283–313.

Cappa, S. D., Sandrini, M., Rossini, P. M., Sosta, K., & Miniussi, C. (2002). The role of the left frontal lobe in action naming: rTMS evidence. *Neurology, 59*, 720–723.

Chodorow, M. S. (1979). Time-compressed speech and the study of lexical and syntactic processing. In W. E. Cooper & E. C. T. Walker (Eds.), *Sentence processing: Psycholinguistic studies presented to Merrill Garrett* (pp. 87–111). Hillsdale, NJ: Erlbaum.

Collina, S., Marangolo, P., & Tabossi, P. (2001). The role of argument structure in the production of nouns and verbs. *Neuropsychologia, 39*, 1125–1137.

Coltheart, M. (1981). The MRC psycholinguistic database. *Quarterly Journal of Experimental Psychology, 33A*, 497–505.

DeDe, G. (2013). Verb transitivity bias affects on-line sentence reading in people with aphasia. *Aphasiology, 27*(3), 326–343.

Den Ouden, D. B., Fix, S., Parrish, T. B., & Thompson, C. K. (2009). Argument structure effects in action verb naming in static and dynamic conditions. *Journal of Neurolinguistics, 22*(2), 196–215.

Edmonds, L., Nadeau, S., & Kiran, S. (2009). Effect of verb network strengthening treatment (VNeST) on lexical retrieval of content words in sentences in persons with aphasia. *Aphasiology, 23*(3), 402–424.

Edwards, S., & Bastiaanse, R. (1998). Diversity in the lexical and syntactic abilities of fluent aphasic speakers. *Aphasiology, 12*, 99–117.

Fertonani, A., Rosini, S., Cotelli, M., Rossini, P. M., & Miniussi, C. (2008). Naming facilitation induced by transcranial direct current stimulation. *Behavioural Brain Research, 208*(2), 311–318.

Fischer-Baum, S., Dickson, D. S., & Federmeier, K. D. (2014). Frequency and regularity effects in reading are task dependent: Evidence from ERPs. *Language, Cognition and Neuroscience, 29*, 1342–1355.

Fodor, J. A., Garrett, M., & Bever, T. G. (1968). Some syntactic determinants of sentential complexity, II: Verb structure. *Perception & Psychophysics, 3*(6), 453–461.

Forman, S. D., Cohen, J. D., Fitzgerald, M., Eddy, W. F., Mintun, M. A., & Noll, D. C. (1995). Improved assessment of significant activation in functional magnetic resonance imaging (fMRI): Use of a cluster-size threshold. *Magnetic Resonance in Medicine, 33*, 636–647.

Friederici, A. D. (2009). Pathways to language: Fiber tracts in the human brain. *Trends in Cognitive Sciences, 13*, 175–181.

Friederici, A. D. (2011). The brain basis of language processing: From structure to function. *Physiological Reviews, 91*(4), 1357–1392.

Friederici, A. D., & Kotz, S. A. (2003). The brain basis of syntactic processes: Functional imaging and lesion studies. *Neuroimage, 20*, S8–S17.

Friston, K. J., Worsley, K. J., Frackowiak, R. S. J., Mazziotta, J. C., & Evans, A. C. (1994). Assessing the significance of focal activations using their spatial extent. *Human Brain Mapping, 1*, 210–220.

Gold, B. T., & Buckner, R. L. (2002). Common prefrontal regions co-activate with dissociable posterior regions during controlled semantic and phonological tasks. *Neuron, 35*, 803–812.

Hale, K. L., & Keyser, S. J. (2002). *Prolegomenon to a theory of argument structure*. Cambridge, MA: MIT Press.

Havas, V., Gabarrós, A., Juncadella, M., Rifa-Ros, X., Plans, G., Acebes, J. J., ... Rodríguez-Fornells, A. (2015). Electrical stimulation mapping of nouns and verbs in Broca's area. *Brain & Language, 145–146*, 53–63.

Hernandez, M., Fairhall, S. L., Lenci, A., Baroni, M., & Caramazza, A. (2014). Predication drives verb cortical signatures. *Journal of Cognitive Neuroscience, 26*(8), 1829–1839.

Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition, 92*(1–2), 67–99.

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience, 8*(5), 393–402.

Holmes, V. M., & Forster, K. I. (1970). Detection of extraneous signals during sentence recognition. *Attention, Perception & Psychophysics, 7*(5), 297–301.

Hoyle, M. H. (1973). Transformations—An introduction and a bibliography. *International Statistical Review, 41*(2), 203–223.

Ahrens, K., & Swinney, D. (1995). Participant roles and the processing of verbs during sentence comprehension. *Journal of Psycholinguistic Research, 24*(6), 533–547.

Kamide, Y. (2008). Anticipatory processes in sentence processing. *Language and Linguistics Compass, 2*(4), 647–670.

Kielar, A., Meltzer-Asscher, A., & Thompson, C. K. (2012). Electrophysiological responses to argument structure violations in healthy adults and individuals with agrammatic aphasia. *Neuropsychologia, 50*, 3320–3337.

Kim, M., & Thompson, C. K. (2000). Patterns of comprehension and production of nouns and verbs in agrammatism: Implications for lexical organization. *Brain and Language, 74*(1), 1–25.

Levin, B. (1993). *English verb classes and alternations: A preliminary investigation*. Chicago, IL: University of Chicago Press.

Levin, B., & Rappaport-Hovav, M. (1994). *Unaccusativity: At the syntax-lexical semantics interface*. Cambridge, MA: MIT Press.

Malyutina, S., & Den Ouden, D. (2015). High-definition tDCS of noun and verb retrieval in naming and lexical decision. *NeuroRegulation, 2*(3), 111–125.

Marangolo, P., Fiori, V., Di Paola, M., Cipollari, S., Razzano, C., Oliveri, M., & Caltagirone, C. (2013). Differential involvement of the left frontal and temporal regions in verb naming: A tDCS treatment study. *Restorative Neurology and Neuroscience, 31*, 63–72.

Marshall, J. (1995). The mapping hypothesis and aphasia therapy. *Aphasiology, 9*, 517–539.

Medler, D. A., & Binder, J. R. (2005). MCWord: An On-Line Orthographic Database of the English Language. <http://www.neuro.mcw.edu/mcword/>.

Meltzer-Asscher, A., Mack, J. E., Barbieri, E., & Thompson, C. K. (2015). How the brain processes different dimensions of argument structure complexity: Evidence from fMRI. *Brain & Language, 142*, 65–75.

Meltzer-Asscher, A., Schuchard, J., Den Ouden, D.-B., & Thompson, C. K. (2013). The neural substrates of complex argument structure representations: Processing 'alternating transitivity' verbs. *Language and Cognitive Processes, 28*, 1154–1168.

Meyer, L., Obleser, J., Kiebel, S. J., & Friederici, A. D. (2012). Spatiotemporal dynamics of argument retrieval and reordering: An fMRI and EEG study on sentence processing. *Frontiers in Psychology, 3*, 523.

Piñango, M., & Deo, A. (2015). Reanalyzing the complement coercion effect through a generalized lexical semantics for aspectual verbs. *Journal of Semantics*. http://dx.doi.org/10.1093/jos/ffv003.

Ramchand, G. (2014). Creating a productive space for theory and experimentation. In A. Bachrach, I. Roy, & L. Stockall (Eds.), *Structuring the argument: Multidisciplinary research on verb argument structure* (pp. 185–200). John Benjamins Publishing Company.

Rappaport Hovav, M., & Levin, B. (1998). Building verb meanings. In M. Butt & W. Geuder (Eds.), *The projection of arguments* (pp. 97–134). Stanford, CA: CSLI Publications.

Rice, S. (1988). Unlikely lexical entries. In S. A. A. Jaisser & H. Singmaster (Eds.), *Proceedings of the 14th annual berkeley linguistics society* (pp. 202–212). Berkeley: Berkeley Linguistics Society.

Rochon, E., Laird, L., Bose, A., & Scofield, J. (2005). Mapping therapy for sentence production impairments in nonfluent aphasia. *Neuropsychological Rehabilitation, 15*(1), 1–36.

Rodriguez-Ferreiro, J., Llorenc, A., & Sanz-Torrent, M. (2014). Argument structure and the representation of abstract semantics. *PlosOne, 9*(8).

Rudanko, J. (1996). *Prepositions and complement clauses: A syntactic and semantic study of verbs governing prepositions and complement clauses in present-day english*. Albany, NY: State University of New York Press.

Russo, K. D., Peach, R. K., & Shapiro, L. P. (1998). Verb preference effects in the sentence comprehension of fluent aphasic individuals. *Aphasiology, 12*, 537–545.

Seghier, M. (2013). The angular gyrus: Multiple functions and multiple subdivisions. *Neuroscientist, 19*(1), 43–61.

Shapiro, L. P., Brookins, B., Gordon, B., & Nagel, N. (1991). Verb effects during sentence processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17*(5), 983–996.

Shapiro, L. P., Gordon, B., Hack, N., & Killackey, J. (1993). Verb-argument structure processing in complex sentences in Broca's and Wernicke's aphasia. *Brain and Language, 45*(3), 423–447.

Shapiro, L. P., Zurif, E., & Grimshaw, J. (1987). Sentence processing and the mental representation of verbs. *Cognition, 27*(3), 219–246.

Shapiro, L. P., Zurif, E., & Grimshaw, J. (1989). Verb processing during sentence comprehension: Contextual impenetrability. *Journal of Psycholinguistic Research, 18*(2), 223–243.

Shetreet, E. (2014). Between linguistics and neuroimaging. In A. Bachrach, I. Roy, & L. Stockall (Eds.), *Structuring the argument: Multidisciplinary research on verb argument structure* (pp. 169–183).

Shetreet, E., Friedmann, N., & Hadar, U. (2010). Cortical representation of verbs with optional complements: The theoretical contribution of fMRI. *Human Brain Mapping, 31*(5), 770–785.

Shetreet, E., Palti, D., Friedmann, N., & Hadar, U. (2007). Cortical representation of verb processing in sentence comprehension: Number of complements, subcategorization and thematic frames. *Cerebral Cortex, 17*, 1958–1969.

Thompson, C. K. (2003). Unaccusative verb production in agrammatic aphasia: The argument structure complexity hypothesis. *Journal of Neurolinguistics, 16*(2–3), 151–167.

Thompson, C. K., Bonakdarpour, B., & Fix, S. F. (2010). Neural mechanisms of verb argument structure processing in agrammatic aphasic and healthy age-matched listeners. *Journal of Cognitive Neuroscience, 22*(9), 1993–2011.

Thompson, C. K., Bonakdarpour, B., Fix, S. C., Blumenfeld, H. K., Parrish, T.-B., Gitelman, D. R., & Mesulam, M. M. (2007). Neural correlates of verb argument structure processing. *Journal of Cognitive Neuroscience, 19*(11), 1753–1767.

Thompson, C. K., Lange, K. L., Schneider, S. L., & Shapiro, L. P. (1997). Agrammatic and non-brain-damaged subjects' verb and verb argument structure production. *Aphasiology, 11*(4/5), 473–490.

Thompson, C. L., & Meltzer-Asscher, A. (2014). Neurocognitive mechanisms of verb argument structure processing. In A. Bachrach, I. Roy, & L. Stockall (Eds.), *Structuring the argument: Multidisciplinary research on verb argument structure* (pp. 141–168). John Benjamins Publishing Company.

Thompson, C. K., Riley, E. A., Den Ouden, D. B., Meltzer-Asscher, A., & Lukic, S. (2013). Training verb argument structure production in agrammatic aphasia: Behavioral and neural recovery patterns. *Cortex, 49*(9), 2358–2376.

Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National academy of Sciences of the United States of America, 94*(26), 14792–14797.

Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Étard, O., Delcroix, N., ... Joliot, M. (2002). Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. *NeuroImage, 15*, 273–289.

Whitworth, A., Webster, J., & Howard, D. (2015). Argument structure deficit in aphasia: It's not all about verbs. *Aphasiology*. http://dx.doi.org/10.1080/02687038.2015.1037823.

Wright, S. K. (2002). Transitivity and change of state verbs. *Berkley Linguistics Society, 28*, 339–350.