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Heterogeneity in abstract verbs: An ERP study

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ABSTRACT

It has been well documented that different types of nouns and action verbs are associated with behavioral and neural differences. In contrast, abstract verbs (e.g., *think*, *dissolve*) are often treated as a homogeneous category. We compared event-related potentials recorded during a syntactic classification task of four verb types; 1) abstract mental, 2) abstract emotional, 3) abstract nonbodily, and 4) concrete. Abstract nonbodily state verbs showed a sustained negativity at frontocentral electrodes and sustained positivity at parietal and occipital electrodes beginning 400 ms post-stimulus onset relative to abstract mental state and concrete verbs. Discrete source localization revealed a right inferior parietal source for all verbs and a distributed source estimation localized sources that distinguished between abstract mental state and abstract nonbodily state verbs to bilateral parietal cortex, left temporal cortex and right ventromedial prefrontal cortex. These findings suggest that different types of abstract verbs are associated with representational differences.

1. Introduction

Over the past two decades researchers in the field of psycholinguistics have been active testing proposals derived from embodied cognition, and in particular investigating the role of sensorimotor information in semantic representation. Theories of semantic representation can be placed along a continuum (Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012); from unembodied amodal theories, which propose that semantic processing is based solely on symbolic representations with no relationship to the sensorimotor experience originally associated with a concept (Newell & Simon, 1976; Pylyshyn, 1980), to fully embodied theories which propose that semantic processing is wholly reliant on simulations of sensorimotor experience associated with a concept (Glenberg, 2015; Lakoff & Johnson, 1999). Mounting evidence supports hybrid theories, which fall between these two ends of the continuum, proposing that concepts have flexible, multi-modal representations that rely on a variety of simulated sensorimotor, linguistic and introspective experiences, dependent on the type of word and the context (Barca, Mazzuca, & Borghi, 2017; Barsalou, Santos, Simmons, & Wilson, 2008; Barsalou & Wiemer-Hastings, 2005; Borghi et al., 2017; Harpaintner, Trumpp, & Kiefer, 2018; Harpaintner, Sim, Trumpp, Ulrich, & Kiefer, 2020; Hoffman, 2016). In the current study we tested predictions derived from these hybrid theories.

Testing theories of embodied cognition as they relate to semantic processing has been taken up with great interest in neurolinguistics. Thus far, an emphasis has been placed on localizing the neural correlates of action verb processing, with some success. A number of functional magnetic resonance imaging (fMRI) studies have demonstrated that effector-specific areas of the motor and pre-motor cortex are active while participants engage in reading and semantic processing tasks of action verbs that correspond to those effectors (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Desai, Binder, Conant, & Seidenberg, 2010; Hauk, Johnsrude, & Pulvermüller, 2004; Kemmerer, Castillo, Talavage, Patterson, & Wiley, 2008). The functional contribution of this cortical activity has also been investigated with repetitive transcranial magnetic stimulation (rTMS) inhibiting response times for hand-related action verbs when applied to the hand region of the left hemisphere motor cortex (Repetto, Colombo, Cipresso, & Riva, 2012) and TMS to the effector-specific areas of the motor cortex facilitating response times to effector-specific action verbs (Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005).

In addition, electroencephalography (EEG) studies have supported a distinct neural electrophysiological pattern for concrete compared to abstract concepts, with concrete nouns eliciting more negative amplitudes at central and frontal electrode sites approximately 400 ms post-stimulus (N400; Amsel & Cree, 2013). Action verbs have been

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associated with higher bilateral activation in sensorimotor regions 155–174 ms post-stimulus compared to non-action verbs using source reconstruction on event-related potentials (ERPs; Vanhoutte et al., 2015). An investigation of the spatial and temporal dynamics of ERPs related to processing either action verbs (foot, mouth, or hand) or abstract verbs has provided evidence of distinct regions of neural activity (Dalla Volta, Fabbri-Destro, Gentilucci, & Avanzini, 2014). Concrete verbs were associated with greater activity in the sensorimotor area of the right hemisphere during early processing and greater activation in the parietal lobe of the left hemisphere during later processing intervals. Abstract verbs, on the other hand, were associated with greater activation outside the sensorimotor regions at both early and late processing intervals, in the pre-frontal cortex.

While substantial progress has been made in understanding how semantic meaning for action language is represented, it has been difficult to account for representation of other kinds of concepts and early investigations of semantic representation and embodied cognition focused on the seemingly dichotomous representation of concrete versus abstract concepts. Theoretical accounts have more difficulty explaining the representation of abstract concepts, and in particular verb concepts, largely due to the fact that verbs tend to be rated as less concrete than nouns (Bird, Franklin, & Howard, 2001). Hybrid theories of semantic processing provide greater opportunity to address abstractness. For example, some hybrid theories propose that conceptual representation relies on a combination of grounded and linguistic experience (e.g., Barsalou et al., 2008; Borghi & Binkofski, 2014). Multidimensional theories take this further to consider how dimensions related to word meaning interact under different task conditions, as the information recruited in any given situation is task or context dependent (e.g., Goh, Yap, Lau, Ng, & Tan, 2016; Yap, Pexman, Wellsby, Hargreaves, & Huff, 2012). Such theories allow us to consider that different kinds of abstract concepts may rely on different underlying representational systems, with reliance on any given system varying based on the nature of the particular concept and the context in which it is processed. Recently there has been a new focus on identifying discrete types of abstract concepts and their associated dimensions, and this heterogenous approach to abstract concept investigation has been fruitful in testing predictions derived from such theories.

Dreyer and Pulvermüller (2018) investigated modality-specific activations during the processing of abstract emotional nouns, abstract mental nouns and concrete nouns (tools and food items). Abstract mental nouns activated mouth regions of the motor cortex to a greater degree than hand regions, and were also associated with activation in classic language areas such as Broca's area, the posterior middle and inferior temporal gyrus, fusiform gyrus and precentral cortex. Previous evidence from Dreyer et al. (2015) has also linked activation of the motor cortex with processing abstract emotional concepts, and lesion case studies indicate that the motor cortex plays a causal role in processing these concepts. These studies support a view that abstract language engages multimodal representations, in this case motor representations, alongside typical linguistic processing.

Further, Harpaintner et al. (2018) conducted a behavioral cluster analysis which differentiated abstract concepts based on associated modality-specific properties. They found one cluster of abstract concepts that had a high proportion of motor-related properties and another with a high proportion of visual properties. A subsequent study investigated whether modality-specific neural activation was evident during the processing of abstract words with more motor-related features and more visual-related features (Harpaintner et al., 2020). Indeed, neural activity associated with processing motor abstract words matched activity observed during hand movements and neural activity associated with processing visual abstract words matched that observed during an object perception task. These findings suggest that abstract concepts with sensorimotor properties may engage modality-specific neural regions during processing and can be differentiated based on those modalities.

Additional insight comes from a recent study by Villani, Lugli, Liuzza, and Borghi (2019), who examined Italian abstract words by collecting word ratings on a variety of dimensions and conducting a principal components analysis of those ratings to extract latent factors used to identify clusters of abstract concepts. Abstract concepts were found to fit within four different clusters defined by Villani et al. as: physical, spatio-temporal and quantitative concepts, self and sociality concepts, philosophical/spiritual concepts, and emotional/inner state concepts. The findings of another study, comparing patients with Alzheimer's disease to those with primary progressive aphasia (Catricalà, Della Rosa, Plebani, Vigliocco, & Cappa, 2014), further support heterogeneity amongst abstract concepts, since primary progressive aphasia patients demonstrated impaired processing in social abstract concepts compared to patients with Alzheimer's Disease who were impaired in all abstract concepts other than emotional abstract concepts. These findings support hybrid theories which propose that abstract concepts are grounded in multiple types of experience, which may include sensorimotor experience, but are also augmented by social, linguistic, emotional, and introspective experiences.

Relatively few studies have compared neural activity during the processing of action verbs and specific sub-types of abstract verbs. An fMRI study of English high-, intermediate-, and low-motion verbs and nouns identified the posterior-lateral-temporal cortex (PLTC) as equally engaged in processing of high-motion (e.g., action) verbs, intermediate-motion (e.g., change-of-state and bodily function) verbs and low-motion (e.g., mental state) verbs (Bedny, Caramazza, Grossman, Pascual-Leone, & Saxe, 2008). This shared region of activity was taken as evidence that verbs in general do not utilize sensorimotor-based representations, and rather that brain regions adjacent to those in the PLTC used for motion perception are able to provide bootstrapping for non-grounded representations of both action and abstract verbs.

In contrast, a comparison of English motion and abstract cognition verbs found distinct neural representations for the two verb types, with motion verbs activating left ventral occipital cortex regions relative to cognitive verbs and cognitive verbs activating left posterolateral temporal regions relative to motion verbs (Grossman et al., 2002). Grossman et al. proposed that the former finding suggests some degree of sensorimotor representation during motion verb processing and the latter suggests that abstract verb representation does not utilize sensorimotor systems. Relatedly, a study of Spanish motion, emotional and cognitive verbs supports a partial distinction of neural activation associated with abstract and action verbs (Rodriguez-Ferreiro, Gennari, Davies, & Cuetos, 2010), however, abstract verbs did display greater activation in inferior frontal, anterior and posterior temporal regions relative to the concrete motion verbs. Providing further support for distinct representational systems amongst abstract verbs, Ghio, Vaghi, Perani, and Tettamanti (2016) conducted an fMRI investigation of three types of abstract (mental state, emotion, and mathematical) and three types of concrete (mouth, hand, and leg action) Italian words presented in sentences. A multivariate pattern analysis (MVPA) revealed specific activity patterns for each of the six sentence types that emerged consistently across participants, with the left inferior frontal gyrus and bilateral insular lobes in particular contributing to a better than chance ability for the MVPA classifier to distinguish between all sentence types. Though these activity patterns did not include any experiential regions predicted by embodied theories of semantic representation, Ghio et al. proposed that the patterns of observed activity in the left inferior frontal gyrus could correspond to specific sub-regions that are implicated in processes of verbal language or non-verbal social interactions and empathy.

While a shifted focus to heterogenous categories of abstract words has proven a welcome departure from the previous abstract/concrete dichotomy, the current evidence regarding the neural correlates of abstract verb representation is inconsistent and investigations of English verbs have covered a limited range of abstract verb types. For instance, the existing studies of abstract verb representation have only included verb concepts that relate in some way to human bodily experience, whether action-based, emotional, or introspective. However, there are several abstract verbs that refer to actions which initiate a change of state that occurs *external* to the human body (e.g., *dissolve*, *sweeten*). Inclusion of such a category into our investigations could help better define the continuum of concrete to abstract verb representation, from the arguably most embodied action verbs to those with no direct associations to human physical, mental, or emotional experience. Furthermore, all investigations to date have used fMRI; however, the time course of language processing (and in particular single-word processing) lends itself well to the fine-grained temporal resolution of EEG and ERP, allowing us to identify both spatial and temporal distinctions that underlie abstract verb processing.

To close this gap, we investigated distinctions in neural activity between three types of abstract verbs: verbs that refer to mental states of being, verbs that refer to emotional states of being and verbs that have no apparent relationship to a human bodily experience, identified as nonbodily state verbs. These abstract verb types reflect the various representational systems outlined by hybrid models of semantic representation: introspective grounding (mental state verbs), affective grounding (emotional state verbs) and linguistic grounding (nonbodily state verbs). Previous evidence suggests that both abstract mental and emotional state verbs may be associated with activity similar to concrete verbs, including the left sensorimotor cortex and specifically facial regions of the motor cortex for mental state abstract words alone (Dreyer & Pulvermüller, 2018; Dreyer et al., 2015). Given previous research, it is possible that only nonbodily state abstract verbs may demonstrate different patterns of activity than concrete verbs. This may emerge in EEG as a negative N400 ERP component situated at frontal and central electrodes for mental and emotional state abstract verbs in addition to concrete verbs (Amsel & Cree, 2013). Furthermore, mental and emotional state abstract verbs may share sources in the sensorimotor and parietal cortex with concrete verbs (Dalla Volta et al., 2014).

A syntactic categorization task was used, in which participants were asked to consider whether each presented word is a verb; this task engages semantic processing and encouraged participants to focus on verb features that exist amongst all the word types of interest in the study. We used a go/no-go design, wherein participants were instructed to respond as quickly as possible if a target stimulus is presented, but to withhold a response if a different stimulus is presented. Go/no-go designs have several advantages over other types of categorization tasks, including greater response accuracy and fewer processing demands (Perea, Rosa & Gómez, 2002). An inhibition effect in the P3 ERP component has been observed in go/no-go tasks, however this effect is only observed in no-go trials (Smith, Jamadar, Provost, & Michie, 2013). Given that our main interest was in contrasting verb types, and all verbs trials are go trials, we expected that any inhibition effect should not differ between abstract verb types.

In light of the conflicting evidence from previous neuroimaging studies and a paucity of research on ERP components related to English abstract verb processing, we investigated differences in ERP components and source estimates for each verb type using a data-driven multivariate analysis approach to identify patterns of electrical activity that co-vary together according to the four verb types (Lobaugh, West, & McIntosh, 2001). Partial Least Squares (PLS) analysis offers an objective approach to identify the strongest observable effects both spatially and temporally. It tests the strength of those effects via permutation tests and the reliability of those effects using bootstrap estimations of the standard error. Thus, it provides an objective, rigorous method of identifying spatial and temporal differences amongst our verb types which is well suited to the exploratory nature of this study. To follow-up any significant differences identified by the PLS analysis, source modeling analysis was used to locate generators related to those distinct patterns of neural activity.

If abstract verbs rely on heterogenous representations, as hybrid and multiple representational theories would posit, we anticipated that there would be different patterns of neural activity amongst abstract verb types, and that these differences in neural activity would be associated with different neural generators. For instance, abstract mental and emotional state verbs may share motor cortex sources with concrete verbs, whereas abstract nonbodily state verbs may rely solely on sources in the classic language processing regions of the left temporal lobe. Differences in neural activity between abstract verb types could further support hybrid and multimodal theories of semantic representation, by suggesting that these concepts combine different underlying representation systems involving modalities related to the semantic content of the abstract words and non-modal linguistic representations.

2. Method

2.1. Participants

Fifty-six participants (37 female; mean age 24.11 years old; SD = 6.68) took part in the study. Participants were undergraduates at the University of Calgary who participated in exchange for bonus credit in a psychology course or in exchange for monetary compensation of $40 if they were not enrolled in a course that allowed for bonus credit. All participants were fluent in English, right-handed, with no history of head trauma (e.g., concussions, comas, etc.), no dental implants, were not using psychotropic medications and had normal or corrected-to-normal vision.

2.2. Stimuli

The stimuli included 140 verbs (four sets of 35 words) and 120 nouns (two sets of 60 words). Noun stimuli were included because the task required negative exemplars of the “is it a verb?” decision. That is, we expected that participants would make “yes” decisions to the verb stimuli and “no” decisions to the noun stimuli. As described below, noun stimuli were matched as closely as possible to the verb stimuli so that the decision was based on syntactic class and not on other systematic differences between nouns and verbs. Verb types were defined using three different dimensions; valence ratings (Warriner, Kuperman, & Brysbaert, 2013), embodiment ratings (Sidhu, Kwan, Pexman, & Siakaluk, 2014), and cognitive ratings. Valence ratings were taken from the Warriner, Kuperman, and Brysbaert (2013) norms, where participants were asked to rate the degree to which a word was happy (1) or unhappy (9). The ratings were subsequently reverse-coded so that a low rating indicated unhappy and a high rating indicated happy. Embodiment ratings were taken from the Sidhu, Kwan, Pexman, and Siakaluk (2014) norms, where participants were asked to rate the degree to which a verb referred to an action, state or relation that could easily involve the human body. Low ratings indicate that a verb’s meaning does not easily involve the human body and high ratings indicate that a verb’s meaning easily involves the human body. Cognitive ratings were collected for the present study from a separate group of 25 participants, who were asked to rate 241 low embodiment, neutral valence verbs. Participants were instructed to rate the degree to which each verb was cognitive in nature, with cognitive defined as relating to mental actions or processes of acquiring knowledge and understanding through thought and experience. Participants rated each verb on a scale of 1 (not cognitive) to 7 (fully cognitive). The cognitive ratings are available at osf.io/9tcdv/. The ratings were used to select verbs of four types: concrete verbs, mental state abstract verbs, emotional state abstract verbs and nonbodily state abstract verbs. Concrete verbs were differentiated by significantly higher embodiment ratings than all other verb categories. Emotional state abstract verbs were differentiated by significantly lower (more negative) valence ratings than all other verb categories. Mental and nonbodily state abstract verbs were differentiated from each other as a function of cognitive ratings, with mental state abstract verbs having significantly higher cognitive ratings and nonbodily state abstract verbs having significantly lower cognitive ratings. Nouns were of two different types: high body-object interaction (BOI; Bennett, Burnett, Siakaluk, & Pexman, 2011; Tillotson, Siakaluk, & Pexman, 2008) nouns and low BOI nouns. BOI ratings were used for the nouns to provide an approximate match to the embodiment ratings used to differentiate the verb stimuli. All sets of word stimuli were matched on additional dimensions that have been demonstrated to affect lexical processing (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; Sidhu, Heard, & Pexman, 2016; Yap & Balota, 2009) including: word frequency (log subtitle frequency; Brysbaert & New, 2009), age of acquisition (Kuperman, Stadthagen-Gonzalez, & Brysbaert, 2012) and word length. The descriptive statistics for each word type are presented in Table 1. The complete verb and noun sets are presented in Appendices A and B.

2.3. Procedure

Participants completed a go/no-go syntactic classification task on a computer in a sound-proof, dimly-lit, electrically shielded chamber. They were instructed to look at each presented word and determine if the word is a verb. Stimuli were presented in 28-point Arial font in white letters on a black background using Presentation software (version 18.3; Neurobehavioral Systems Inc., Albany, CA, USA). Participants sat approximately 65 cm away from the computer screen and the words were presented at a vertical viewing angle of 0.87° and a horizontal viewing angle that varied between 1.74° to 9.56° depending on the length of the word. Each trial began with a fixation cross for 500 ms, followed by a blank screen presented at a variable interval of 1–500 ms, and then a word was presented at the centre of the screen for up to 5,000 ms. Participants were instructed to withhold their response for 2,000 ms in order to eliminate motor artifacts in the critical period of word processing post-stimulus in the EEG recording. Following the 2,000 ms, a "Yes" appeared in the bottom right corner of the screen for 3,000 ms or until the participant made a response. Participants were asked to respond as quickly and accurately as possible after the "Yes" appeared on screen by pressing the "k" key on the keyboard if the word was a verb and withholding a response if the word was not a verb. They received 10 practice trials with feedback prior to beginning the experiment.

2.4. EEG data recording and pre-processing

Scalp potentials were recorded from 64 cap embedded electrodes arranged in the international 10–20 electrode positioning format, with electrode Cz acting as the online reference. BrainVision antiCHamp EEG system with active electrodes (Brain Products GmbH, Gilching, Germany) was used and all electrode impedances were set below 20 kOhms prior to recording.

The data for 20 participants were excluded from analysis. The data for 13 of these participants (collected during the latter half of testing) were removed prior to analysis due to malfunctioning EEG equipment that was discovered after recording, six were removed due to excessive noise in the recorded data and one was removed due to the participant not following task instructions for the majority of trials. For the data of the remaining participants, responses for 133 trials on which response times were more than 3 *SD* away from a participant's mean were excluded from analysis (1.42% of all trials). Additionally, 195 incorrect verb trials (3.87% of all verbs) as well as 276 incorrect noun trials (6.39% of all nouns) were excluded. Finally, for one verb (*beware*) and four nouns (*breach*, *dupe*, *plea*, and *twinge*) response accuracy was lower than 60% across participants, so these words were removed from analysis (48 trials remaining after incorrect trials removed, 0.17% of all trials). After removing these trials 8,708 trials remained in the EEG data for analysis. EEG data were pre-processed using the program EEGLAB (version 14.1.1; Delorme & Makeig, 2004) and ERPLAB (version 6.1.3; Lopez-Calderon & Luck, 2014). All data were filtered at 0.1–40 Hz. Bad channels were removed and the data were then re-referenced to calculate a common average. We extracted epochs 1,200 ms in length, beginning 200 ms before stimulus presentation and continuing to 1,000 ms post-stimulus. Epochs were baseline corrected from the first 200 ms portion of the epoch. Noisy epochs were removed based on visual inspection and artifact removal was completed using independent components analysis (ICA). Components related to motor activity such as eye blinks, saccades and horizontal eye movements were removed from the data. After epoch rejection and artifact removal, 7,742 trials remained in the following conditions: mental state abstract verbs (1,042), nonbodily state abstract verbs (1,051), emotional state abstract verbs (1,035), concrete verbs (1,082), low BOI nouns (1,686) and high BOI nouns (1,846). Bad channels were interpolated as the last step of pre-processing.

2.5. PLS analysis method

The ERP data were submitted to a partial least squares (PLS) analysis using the PLS Toolbox for Matlab (Lobaugh et al., 2001; McIntosh, Bookstein, Haxby, & Grady, 1996). Average ERPs for each participant for each word type (verbs and nouns) were extracted from the EEG data. The data matrix was constructed to include one row per participant, per word type. The data consisted of the mean amplitude at each time point, at each electrode, such that each participant × word type row would include data from 64 electrodes at 600 time points. The purpose of the PLS analysis was to use a data-driven approach to identify whole-brain patterns in the ERP waveforms, by extracting covariance amongst the waveforms that can be attributed to the experimental manipulation (in this case, word type) in the form of latent variables. The PLS analysis

Table 1
Descriptive Statistics for Word Stimuli.

Word Type (n = 35 per verb type, 60 per noun type)	Emb. Mean *SD*	Valence Mean *SD*	Freq. Mean *SD*	AoA Mean *SD*	Length Mean *SD*	Cog. Mean *SD*	BOI Mean *SD*
Mental state abstract verbs	3.08	5.99	2.70	8.54	5.86	5.00[c]	n/a
	0.38	*0.34*	*1.00*	*2.41*	*1.44*	*0.57*	
Nonbodily state abstract verbs	3.21	5.98	2.58	8.27	5.57	3.33	n/a
	0.56	*0.32*	*0.97*	*2.15*	*1.24*	*0.54*	
Emotional state abstract verbs	3.13	2.97[b]	2.42	8.51	5.86	n/a	n/a
	0.32	*0.43*	*0.69*	*1.93*	*1.67*		
Concrete verbs	5.01[a]	6.08	2.48	7.82	5.74	n/a	n/a
	0.82	*0.40*	*0.73*	*1.81*	*1.46*		
High BOI Nouns	n/a	5.18	2.51	8.17	5.67	n/a	3.43[d]
		1.27	*0.70*	*2.25*	*1.95*		*0.12*
Low BOI Nouns	n/a	5.60	2.53	8.27	5.50	n/a	1.46
		1.02	*0.84*	*2.76*	*1.49*		*0.22*

Note: Ratings included are embodiment (Emb.), valence, frequency (Freq.), age of acquisition (AoA), length, cognitive (Cog.), and body-object interaction (BOI). Standard deviation = SD. [a] indicates that the embodiment ratings for the cognitive verb type are significantly different than all other word types ($p < .05$). [b] indicates that the valence ratings for the emotional abstract verb type are significantly different than all other word types ($p < .05$). [c] indicates that the cognitive ratings for the cognitive abstract verb type are significantly different from the nonbodily abstract verb type ($p < .05$).[d] indicates that the body-object interaction ratings for the high BOI noun type are significantly different from the low BOI noun type ($p < .05$).

produced task saliences (the degree that each word type is related to the waveform pattern identified by the latent variable) and element saliences (weights that reflect how each electrode at each timepoint contributes to the observed latent variable). The task and element saliences were used to compute brain scores: the summation of the dot product of the task by element salience matrices for each participant and word type. The statistical significance of the latent variables was assessed using permutation tests to determine if the latent variable was better at identifying patterns of activity based on the experimental design compared to random noise, by resampling without replacement observations from different word types while keeping subject constant. The stability of the observed element saliences for each latent variable was tested using bootstrap samples, by resampling with replacement observations from different subjects while keeping word type constant. For all PLS analyses reported here we used 1,000 permutations and 1,000 bootstraps. For the current paper we show the full range of bootstrap ratios. Otherwise we designated a threshold of 2.0, corresponding roughly to a 95% confidence interval or a *p*-value less than 0.05. We use different bootstrap thresholds to highlight the timeframe of stable differences.

2.6. Source modeling & estimation

We conducted a discrete source analysis using Brain Electrical Source Analysis (BESA; version 6.1; Gräfelfing, Germany) software package and a distributed source estimation using Brainstorm (Tadel, Baillet, Mosher, Pantazis, & Leahy, 2011) software package.

For the discrete source analysis, the regularization constant was set at 1% (program default) to stabilize source fitting results in the presence of noise and reduce interaction amongst dipoles. The distance criterion was set to 8 mm to prevent crosstalk between source waveforms. A four-shell ellipsoidal head model was used, with relative conductivities of 0.33 (head), 0.33 (scalp), 0.0042 (bone), and 1 (cerebrospinal fluid; CSF). The thickness of the scalp, bone and CSF were set to 6 mm, 7 mm, and 1 mm (thickness), respectively, and the head radius was set to 85 mm. Dipole modeling was conducted across the waveform time range (0 ms – 1,000 ms post stimulus presentation). To account for visual effects related to visually presented stimuli, a pre-existing BESA source montage for tasks using visual stimuli was used. Additional sources were fit using a drop-in/drop-out method until added sources no longer explained at least 1% incremental variance in the data. This process resulted in a single dipole being added to the original seven sources in the visual-evoked potential source montage.

As a follow-up to the discrete source analysis, we conducted a distributed source estimation to identify the contribution of sources to the observed scalp distribution from 58 pre-defined regions of interest (ROI) of the cerebral cortex defined in Talairach space (Diaconescu, Alain, & McIntosh, 2011; Wang, McIntosh, Kovacevic, Karachalios, & Protzner, 2016). The source estimation was constructed using the minimum norm imaging method and the resulting estimates were normalized using sLORETA (Pascual-Marqui, 2002). Source estimates were constrained to be oriented normally to the cortex surface and the noise covariance regularization was set to 0.1 to increase the robustness of the source estimation to error in the data.

3. Results

Given the imposed response delay to eliminate motor artifacts during the task, no reaction time data were analyzed, as they do not accurately reflect processing speed. Mean response accuracies by word type are presented in Table 2. A linear mixed effects model with a fixed effect of word class (verb, noun) and a random effect of subject showed a significant difference between verbs and nouns, $t(179) = -8.46$, $p < .001$, with nouns showing a significantly lower mean accuracy rate (M = 88.99%, SD = 0.09%) than verbs (M = 96.06%, SD = 0.04%). Further linear mixed effects models were fit to assess differences within the noun and verb classes. There was a significant difference in accuracy rates between the high BOI nouns (M = 94.22%, SD = 0.05%) and low BOI nouns (M = 83.75%, SD = 0.08%), $t(35) = -9.11$, $p < .001$. There were no significant differences in response accuracy between the four verb types.

Table 2
Descriptive Statistics for Response Accuracy.

Word Type (n = 35 per verb type, 60 per noun type)	Mean Accuracy (%)	SD (%)
Mental state abstract verbs	96.44	4.80
Nonbodily state abstract verbs	95.52	5.00
Emotional state abstract verb	95.69	4.40
Concrete verbs	96.56	3.61
High BOI Nouns	94.22	5.40
Low BOI Nouns	83.75	8.28

Note: Standard deviation = SD.

3.1. PLS analysis on verb and noun ERPs

Two significant latent variables were identified in the PLS analysis when investigating co-varying patterns in the ERP waveforms amongst all six word types. The first significant latent variable ($p < .001$) highlighted a distinction in activity between verbs and nouns (Fig. 1a). These differences in the waveforms emerged primarily at centrally located electrodes and temporal electrodes, with nouns showing sustained positivity at frontotemporal (FT9, FT10), temporal (T7, T8) and temporoparietal (TP9, TP10) electrodes beginning at ~ 300 ms post-stimulus and sustained negativity at central (FCz, Cz, CPz) electrodes during this same time period (Fig. 1b).

The second significant latent variable (p = .004) highlighted distinctions between concrete verbs and low BOI nouns relative to nonbodily state abstract verbs and high BOI nouns (Fig. 2a). These differences in the waveforms emerged primarily at right, frontal electrodes and bilaterally at posterior, occipital electrodes, with nonbodily verbs and high BOI nouns showing sustained negativity at right frontal electrodes (F5, F1, Fz, F2, F6, FC5, FC1, FCz, FC2, FC6) beginning ~ 350 ms post-stimulus and sustained positivity at bilateral parieto-occipital (PO3, POz, PO4) and occipital (O1, Oz, O2) electrodes beginning between ~ 200 – 400 ms post-stimulus (Fig. 2b and 2c).

3.2. PLS analysis on verb ERPs

When investigating co-varying patterns of neural activity in only the verb types, a single significant latent variable was identified by PLS analysis (p = .009, see Fig. 3a). This latent variable highlighted a distinction in activity between the nonbodily state abstract verbs compared to both mental state abstract verbs and concrete verbs. As demonstrated in the ERP waveforms shown in Fig. 3b, bilateral frontal (AF3, AFz, AF4, F1, Fz, F2) electrodes showed sustained negativity at 400 – 700 ms post-stimulus onset, with larger negative amplitudes for the external, nonbodily state abstract verbs relative to both concrete and mental state abstract verbs. This same effect appeared bilaterally as a sustained positivity for nonbodily state abstract verbs at parieto-occipital (PO3, POz, PO4) and occipital (O1, Oz, O2) electrodes.

3.3. Discrete source localization analysis

To follow-up on the significant differences in ERP activity identified by PLS analysis amongst different verb types we conducted a discrete source localization analysis and a distributed source estimation analysis. The purpose of the discrete source localization was to estimate source waveforms from distinct regions given the distribution of amplitudes recorded at the scalp using our 64-electrode array. The data from all 36 participants for all word types at all electrodes and timepoints were submitted to a single dipole source localization using the dipole model

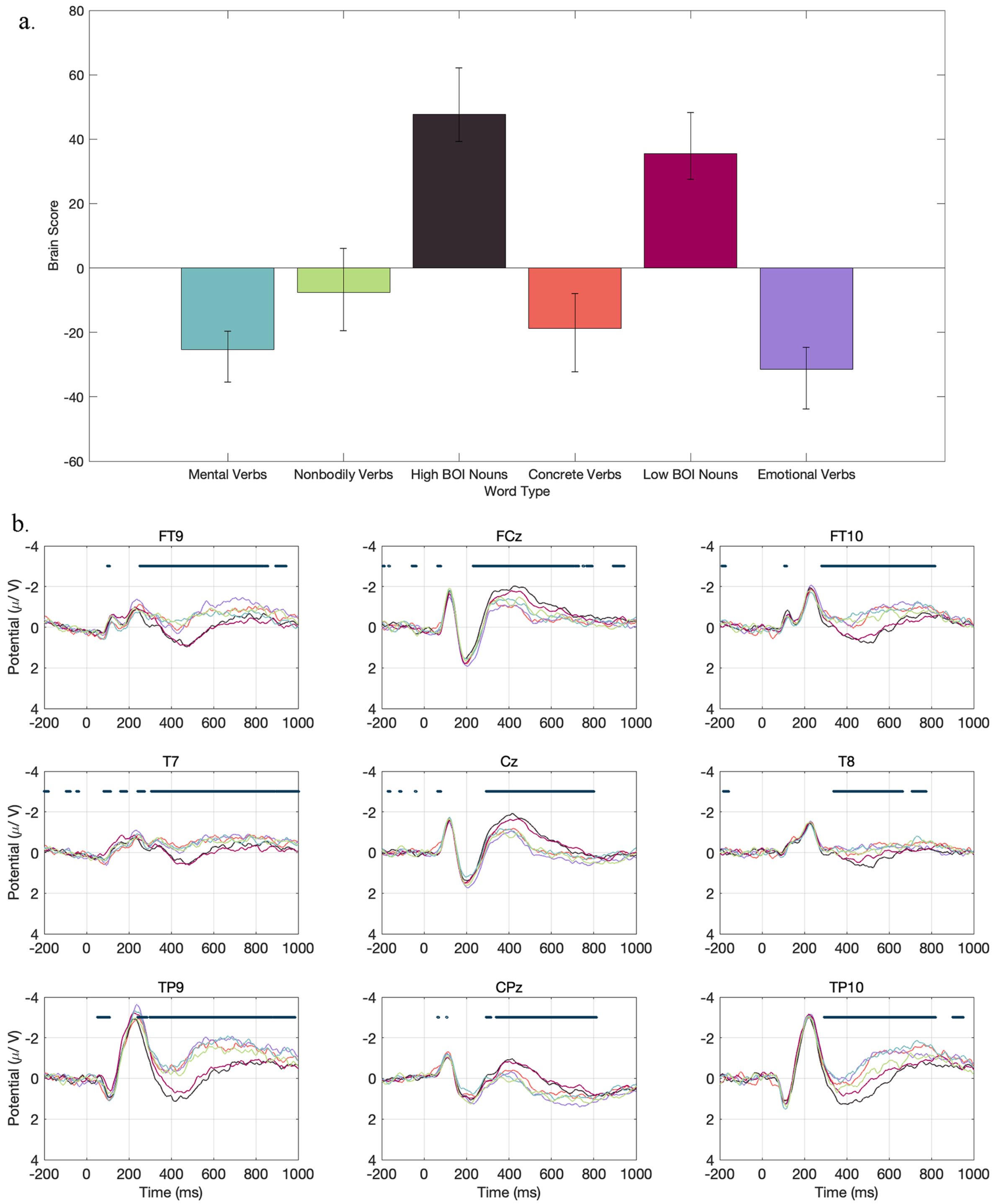

Fig. 1. a. Brain scores for each word type in the first latent variable indicate that, at electrodes and timepoints that are stable as indicated by bootstrap testing, nouns show more positive amplitudes compared to verbs. Error bars represent 95% confidence intervals. b. Grand-averaged ERP waveforms from 9 electrode sites that differ by word type as identified by PLS analysis. Blue dots indicate time points at which stable differences between word types occur, as determined by bootstrapping. Waveform colors correspond to the bars represented in Fig. 1a and negative values are plotted up.

derived from the process described in the methods section. The mean variance accounted for by this model in each condition is presented in Table 3. This led to a source model that added only one right, inferior parietal lobule source (RIPL; Brodmann Area 39), which contributed to the observed scalp amplitudes above and beyond visual cortical regions that would be expected to be active during a reading task (see Fig. 4 and Table 4). A repeated measures ANOVA comparing model residual variance in the source waveforms by word type revealed no significant differences in the amount of variance the model accounted for between word types, $F(5, 175) = 0.61$, $p = .693$. The estimated source waveforms were then extracted and submitted to a PLS analysis, following the same procedure as outlined in the method section (with source location replacing the electrode in the data matrix). The source waveform PLS revealed one significant latent variable ($p < .001$) highlighting a distinction for nonbodily and mental state abstract verbs compared to both emotional state abstract verbs and concrete verbs, as seen in Fig. 5a. Right-lateralized occipital sources (right lateral occipital cortex) and bi-lateral occipital-temporal sources (left occipital-temporal cortex

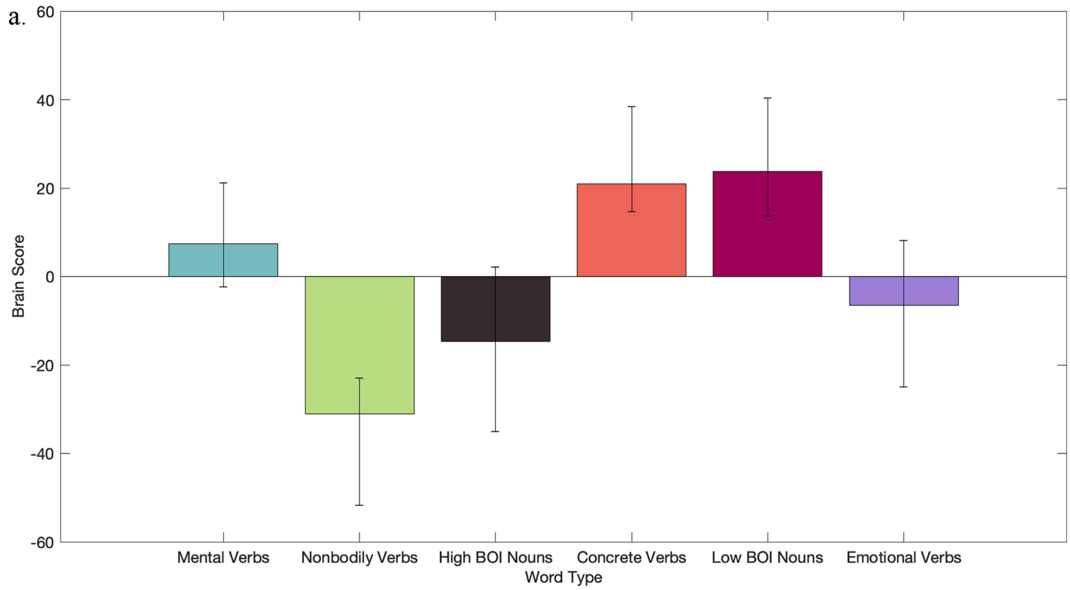

Fig. 2. a. Brain scores for each word type in the second latent variable indicate that, at electrodes and timepoints that are stable as indicated by bootstrap testing, nonbodily state abstract verbs and high BOI nouns show more negative amplitudes compared to concrete verbs and low BOI nouns. Error bars represent 95% confidence intervals. b. Grand-averaged ERP waveforms from 10 frontal electrode sites that differ by word type, as identified by PLS analysis. Blue dots indicate time points at which significant differences between word types occur, with a bootstrap threshold greater than 2, with a corresponding p-value of 0.05. c. Grand-averaged ERP waveforms from 6 posterior electrode sites that differ by word type, as identified by PLS analysis. Blue dots indicate time points at which stable differences between word types occur, as determined by bootstrapping. Waveform colors correspond to the bars represented in Fig. 2a and negative values are plotted up.

and right occipital-temporal cortex) showed greater positivity for nonbodily state abstract verbs when compared to concrete verbs ~ 350–450 ms post-stimulus onset, as shown in Fig. 5b.

3.4. Distributed source localization analysis

To follow-up on some unanticipated sources identified in the discrete source analysis, the data were then submitted to a distributed source estimation. The source estimates for the 58 ROIs were then extracted and submitted to a PLS analysis, following the same procedure as outlined in the Method section (with ROI replacing the electrode in the data matrix). The source estimate PLS revealed one significant latent variable (p = .016) highlighting a distinction between mental state and nonbodily state abstract verbs, as seen in Fig. 6a. Similar to the discrete source analysis, parietal source effects were observed, however, here they emerged in both hemispheres; in the left hemisphere, the primary somatosensory cortex and precuneus showed increases in source estimates for mental state abstract verbs relative to nonbodily state abstract verbs at ~ 400 – 450 ms and ~ 600 – 900 ms post-stimulus onset. In addition, there was an increase in source estimates from the superior parietal cortex for mental state abstract verbs at ~ 350 – 400 ms, ~650–700 ms and ~ 800 – 950 ms post-stimulus onset. In the right hemisphere, there was an increase in source estimates in the primary somatosensory for mental state abstract verbs at ~ 400 ms, ~650 – 700 ms, and 800 – 900 ms post-stimulus onset. In addition, more positive source estimates for mental state abstract verbs were observed ~ 200 – 300 ms in the right precuneus, superior parietal cortex, inferior parietal cortex, and angular gyrus.

Unlike the discrete source analysis, the distributed source analysis revealed differences between mental state and nonbodily state abstract verbs in the frontal and temporal regions of interest. Source estimates in the temporal pole were more positive for mental state abstract verbs relative to nonbodily state abstract verbs bilaterally, at ~ 400 – 850 ms post-stimulus onset. Source estimates were also observed in the inferior temporal cortex, with sustained positive estimates for mental state abstract verbs relative to nonbodily state abstract verbs from ~ 650 – 850 ms post-stimulus onset in the left hemisphere and ~ 400–1,000 ms in the right hemisphere. In contrast, the ventral temporal pole showed bilateral negative source estimates for mental state abstract verbs relative to nonbodily state abstract verbs beginning ~ 300 ms post-stimulus and sustained to the end of the epoch. One source estimate effect was observed in the right frontal cortex, with the right ventrolateral prefrontal cortex showing a sustained negative source estimate for mental state abstract words ~ 350 – 900 ms post-stimulus onset.

Finally, in contrast to the discrete source analysis, only modest effects were identified in the distributed analysis in the occipital regions of interest. In the left secondary visual area source estimates were more positive for mental state abstract words relative to nonbodily state abstract verbs at ~ 550 ms and ~ 700 ms post-stimulus onset. In the right hemisphere earlier differences emerged. Source estimates from the fusiform gyrus were more negative for mental state abstract verbs relative to nonbodily state abstract verbs ~ 200 – 350 ms and source estimates in the cuneus were more positive for mental state abstract verbs relative to nonbodily state abstract verbs from ~ 200 – 300 ms post-stimulus onset.

4. Discussion

The purpose of this study was to investigate differences in neural activity associated with processing of three types of abstract verbs (mental, nonbodily and emotional state) and concrete verbs. Differences in neural activity may indicate reliance on different underlying systems of representation, as predicted by hybrid models of semantic representation. The current findings suggest that there are differences between nonbodily state abstract verbs and concrete verbs, and a consistent difference in neural activity between the mental state abstract and nonbodily state abstract verbs. With PLS analysis on the ERPs from each verb type we found distinctions between nonbodily state abstract verbs relative to mental state abstract verbs and concrete verbs, with a clear pattern of differences in ERP waveforms bilaterally in fronto-central and occipital-parietal electrode locations.

Nonbodily state abstract verbs showed a sustained negativity 400 –

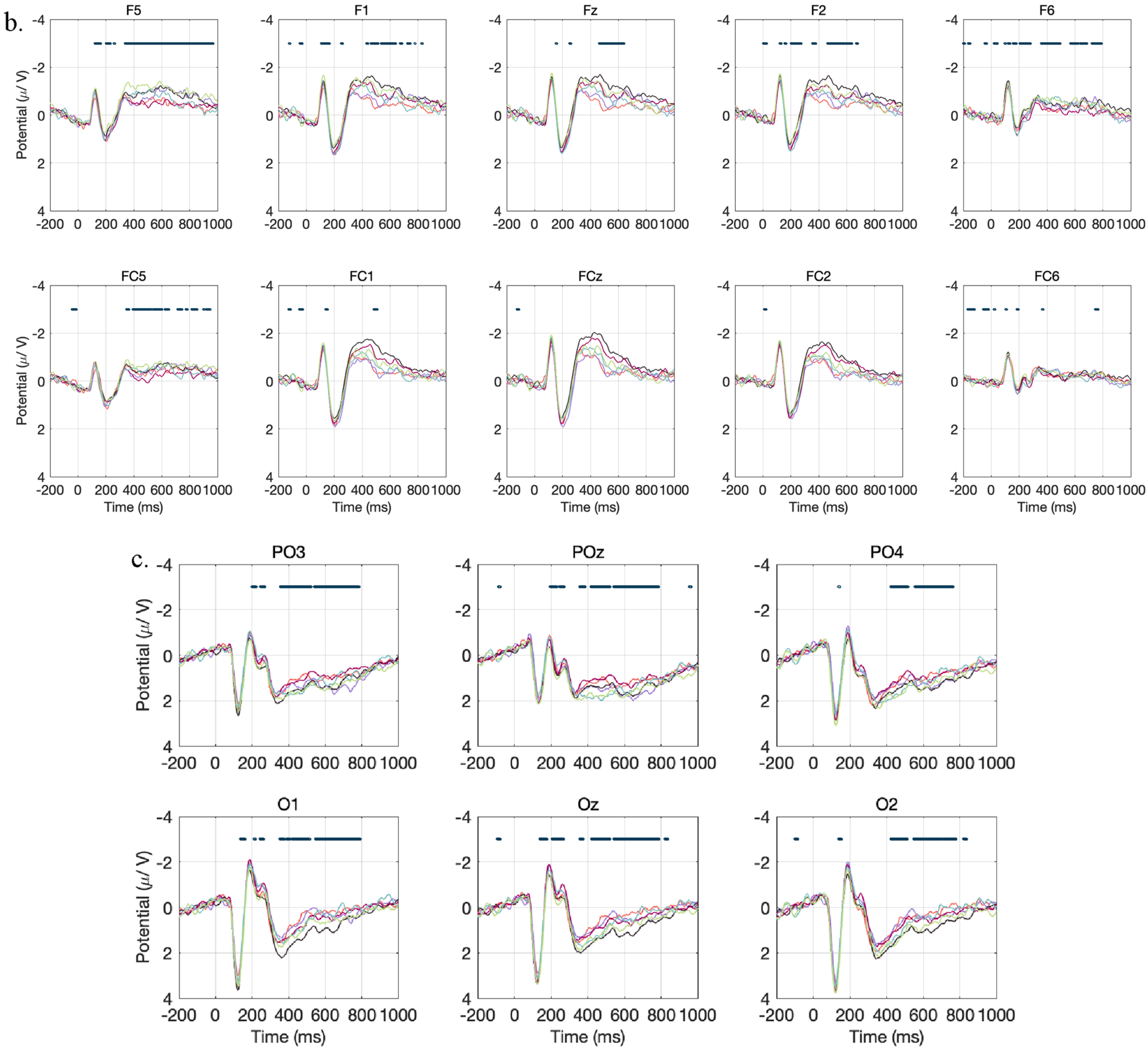

Fig. 2. (*continued*).

700 ms post-stimulus at fronto-central electrodes compared to mental state abstract verbs and concrete verbs. This effect was reversed for the parietal-occipital electrodes, with a more sustained positivity for nonbodily state abstract verbs during the same post-stimulus period. The timing and amplitude of these effects show similarities with two previously identified ERP components that differentiate concrete, metaphorical and abstract language processing: the concreteness N400 (Barber, Otten, Kousta, & Vigliocco, 2013; Dalla Volta et al., 2014; Lai, Howerton, & Desai, 2019) and the embodiment P600 (Bardolph & Coulson, 2014). Typically, more concrete items elicit a larger negative deflection at frontal electrodes relative to abstract items in the N400 concreteness effect, however this negative deflection has also been observed for metaphoric language, with the implication that sensory-motor activation is involved in both concrete and metaphoric processing (Lai et al., 2019). Unique in our results is the finding that greater negativity in the N400 concreteness window is elicited by the nonbodily state abstract verbs *relative* to concrete and mental state abstract verbs. If both concrete and metaphoric language exhibit an N400 due to sensory-motor activation, it would stand to reason that both concrete and abstract verbs should demonstrate this effect too. P600 embodiment effects have been observed wherein metaphoric language elicits larger positive deflections, with the argument that metaphoric language may engage sensorimotor simulations at later stages of processing. This could be reflected in our findings as the sustained positivity observed for nonbodily state abstract verbs at parietal and occipital electrodes, relative to mental state abstract verbs and concrete verbs. However, given the distribution of these effects, and reversal of average amplitude between frontal and parietal sources, it is worth considering whether these reflect a single effect from a distinct dipole source.

To follow-up on this observed effect on the scalp, discrete and distributed source analyses were conducted. The discrete source analysis modeled seven distinct dipoles related to visual processing (used as the base model) and one additional dipole in the right parietal lobule was added to increase the amount of variance accounted for in the observed scalp amplitudes. A PLS analysis on source waveforms for the eight identified sources indicated a right-lateralized source waveform difference between nonbodily state abstract verbs and concrete verbs, with nonbodily state abstract verbs showing a more positive amplitude at

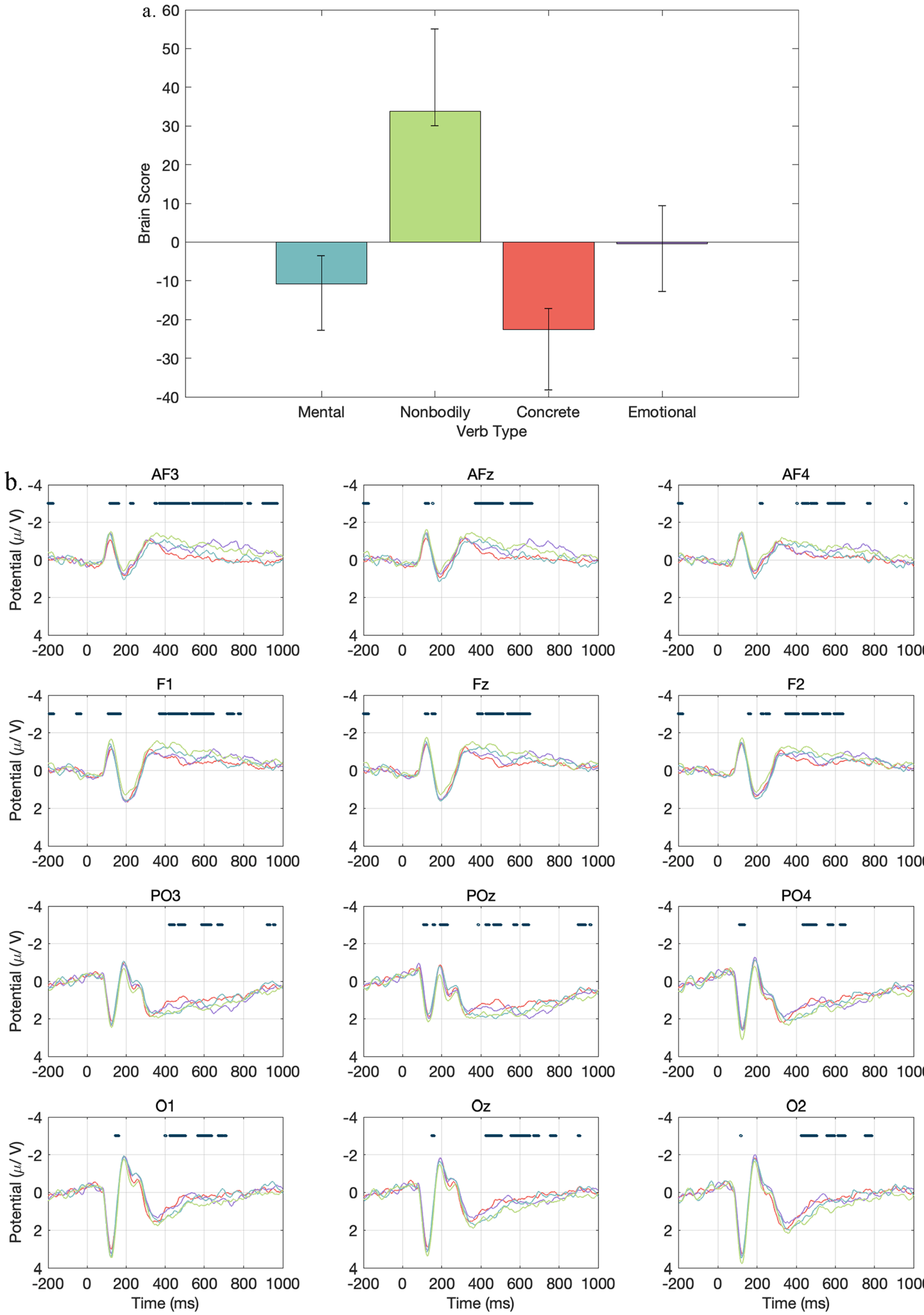

Fig. 3. a. Brain scores for each verb type indicate that, at electrodes and timepoints that are stable as indicated by bootstrap testing, mental state abstract verbs and concrete verbs show more negative amplitudes compared to nonbodily state abstract verbs. Error bars represent 95% confidence intervals. b. Grand-averaged ERP waveforms from 12 electrode sites that differ by verb type, as identified by the PLS analysis. Blue dots indicate time points at which stable differences between word types occur, as determined by bootstrapping. Waveform colors correspond to the bars represented in Fig. 3a and negative values are plotted up.

Table 3
Source model mean variance (R^2) accounted for and standard deviation (SD) by word type (N = 36).

Word Type	R^2	SD
Mental state abstract verbs	66.54%	7.12%
Nonbodily state abstract verbs	66.31%	6.87%
Emotional state abstract verb	65.77%	7.26%
Concrete verbs	66.19%	7.07%
High BOI Nouns	66.12%	7.85%
Low BOI Nouns	65.65%	7.72%

right occipito-temporal sources approximately 350 – 450 ms post-stimulus. Interestingly, the discrete source model was not better at accounting for variance in any of the six word types, indicating that the estimated sources seem to contribute to the observed electrode amplitudes for all word types, including nouns. Given that there are non-significant differences between the two syntactic classes (verbs and nouns), the source model may be identifying sources that are engaged due to the task demands, rather than stimuli properties. Participants were asked to read words and decide if a presented word is a verb. Certainly, the consistent task demand of reading the presented stimuli and the decision participants were required to make could explain the equal variance accounted for by the occipital and parietal sources. The right inferior parietal lobule is typically not identified as a region involved in language processing, however, a study that made a direct comparison of grammatical class effects in fMRI BOLD signal activation found that verbs show significantly greater BOLD signal in the right inferior parietal lobule (Berlingeri et al., 2008). The source activity identified in the right parietal lobe may indicate efforts to associate verbs with the variety of thematic roles within which they can occur (Levin, 1993). Thus, the right inferior parietal lobule may be involved when making decisions about verb category membership, which is precisely the task used in the present study.

The distributed source analysis showed some similarities to the discrete source analysis, however, the simultaneous estimation of 58 ROIs appears to have identified the locus of source activity with more sensitivity than the discrete source analysis model. Although only right-lateralized sources were identified in the discrete source analysis, the distributed source analysis identified both left and right parietal source estimates that were differentially engaged for mental state abstract verbs relative to nonbodily state abstract verbs. The left parietal sources identified in the PLS analysis were more anterior and medial relative to the sources identified in the right hemisphere, which emerged earlier and at more posterior and ventral regions, including the inferior parietal cortex and angular gyrus. The right hemisphere parietal differences detected in the distributed source analysis may indicate that there was increased processing in the verb decision for nonbodily state abstract verbs relative to mental state abstract verbs. This is consistent with the behavioral finding that mental state abstract verbs are associated with faster response times on a syntactic classification task relative to nonbodily state abstract verbs (Muraki, Sidhu, & Pexman, 2020).

The presence of more positive source estimates for mental state and nonbodily state abstract verbs in the primary somatosensory cortex and precuneus offers additional insights. Activity in the somatosensory cortex during language processing has been taken as evidence of modal grounding based on tactile knowledge (Goldberg, Perfetti, & Schneider, 2006) and the precuneus has been implicated in self-consciousness and processing self-related mental representations (Cavanna & Trimble, 2006). It is possible that mental state abstract verbs engage more modal information based on previous tactile experience, as many of the verbs refer to actions that often involve writing or typing such as *edit*, as well as introspective experiences processed in the precuneus.

In contrast to the discrete source analysis, the distributed source analysis identified differences in source estimates bilaterally in the temporal lobe between mental state and nonbodily state abstract verbs, with the temporal pole and inferior temporal cortex showing more positive source estimates for mental state abstract verbs and the ventral temporal cortex showing more negative source estimates for nonbodily state abstract verbs. This aligns to previous fMRI research on cortical regions associated with processing abstract verbs of cognition (Bedny et al., 2008; Grossman et al., 2002; Rodriguez-Ferreiro et al., 2010) and with the results of a *meta*-analysis showing that semantic processing of words encoded using verbal information (in contrast to perceptual information) is associated with activity in the left anterior superior temporal sulcus (Binder et al., 2009).

We found that the nonbodily state abstract verbs showed more positive source estimates in the ventral temporal cortex, which has been associated with processing verbs related to changes of state (Kemmerer et al., 2008). Many of the nonbodily state abstract verbs refer to actions where the changes of state occur to an object *external* to the human body (i.e. transitive verbs) or, as the category name suggests, are not easily

Table 4
Talairach coordinates of sources identified in the source localization model.

Source	x-loc	y-loc	z-loc
R IPL	49.9	−47.9	36.3
R OT	45.2	−57.3	6.7
R LO	25.6	−73.3	4.4
R VO	39.2	−49.3	−22.8
C O	0.9	−86.6	−14.2
L LO	−25.6	−73.3	4.4
L OT	−45.2	−57.3	6.7
L VO	−39.2	−49.2	−22.8

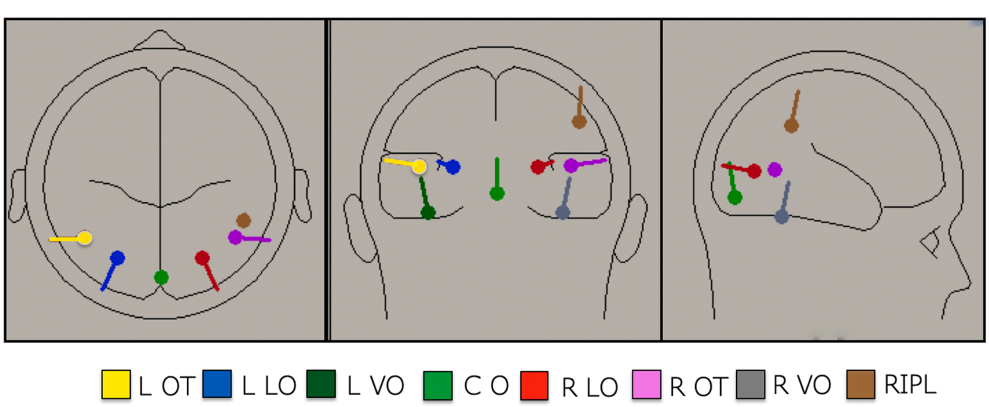

Fig. 4. Source localization results identify a right inferior parietal lobule source alongside occipital cortex sources. L OT = left occipito-temporal cortex, L LO = left lateral occipital cortex; L VO = left ventral occipital cortex; C O = centro-occipital cortex (lingual gyrus); R LO = right lateral occipital cortex; R OT = right occipito-temporal cortex; R VO = right ventral occipital cortex; R IPL = right inferior parietal lobule.

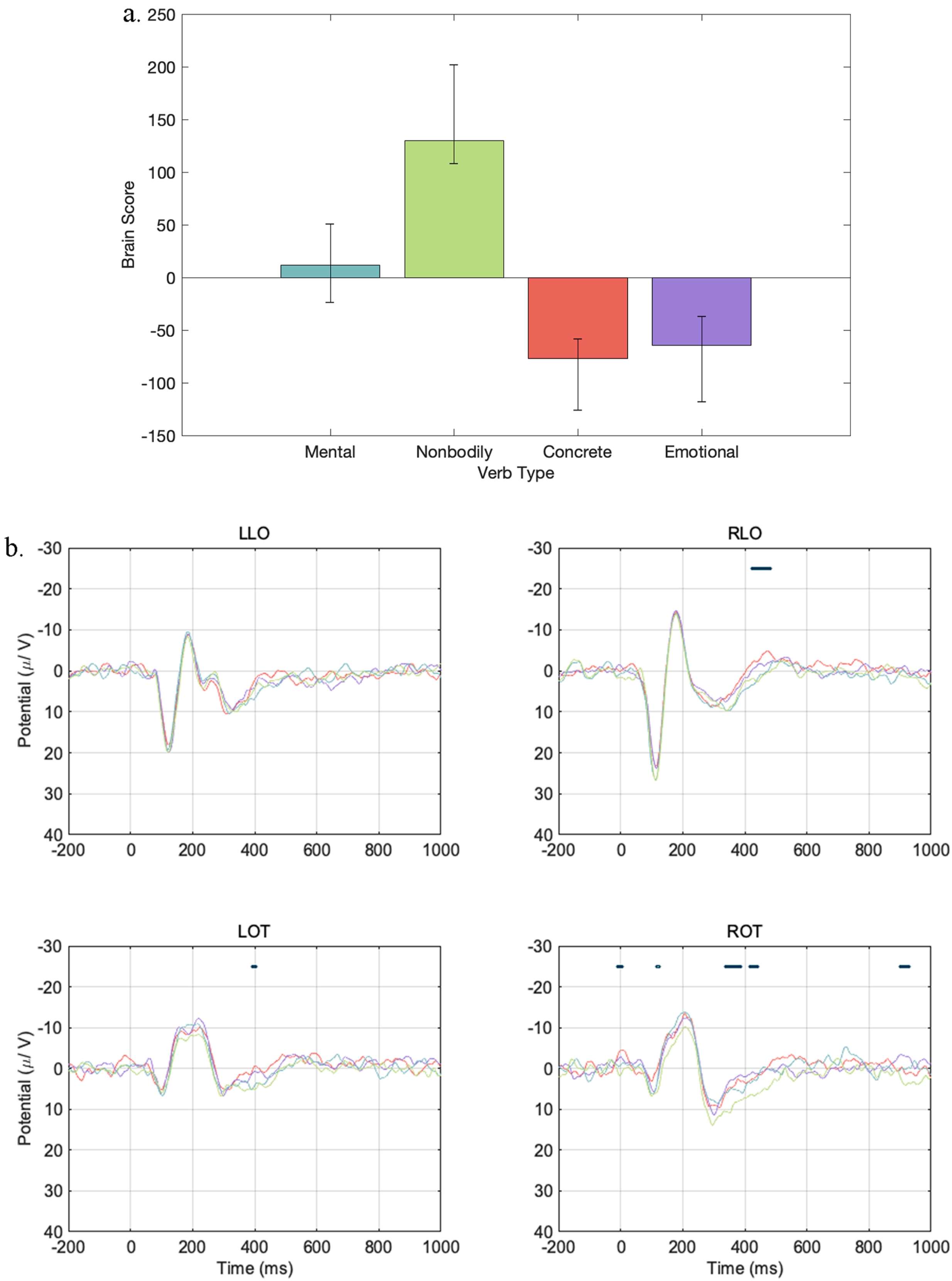

Fig. 5. a. Brain scores for each verb type indicate that, at electrodes and timepoints that are stable as indicated by bootstrap testing, nonbodily and mental state abstract verbs show more positive amplitudes compared to emotional state abstract verbs and concrete verbs. Error bars represented 95% confidence intervals. b. Grand-averaged source waveforms that demonstrate a right-lateralized difference by verb type as identified by the PLS analysis, with nonbodily state abstract verbs showing more positive amplitudes in dorsal, occipital regions. Blue dots indicate time points at which stable differences between word types occur, as determined by bootstrapping. Waveform colors correspond to the bars represented in Fig. 5a and negative values are plotted up. L OT = left occipito-temporal cortex, L LO = left lateral occipital cortex; R LO = right lateral occipital cortex; R OT = right occipito-temporal cortex.

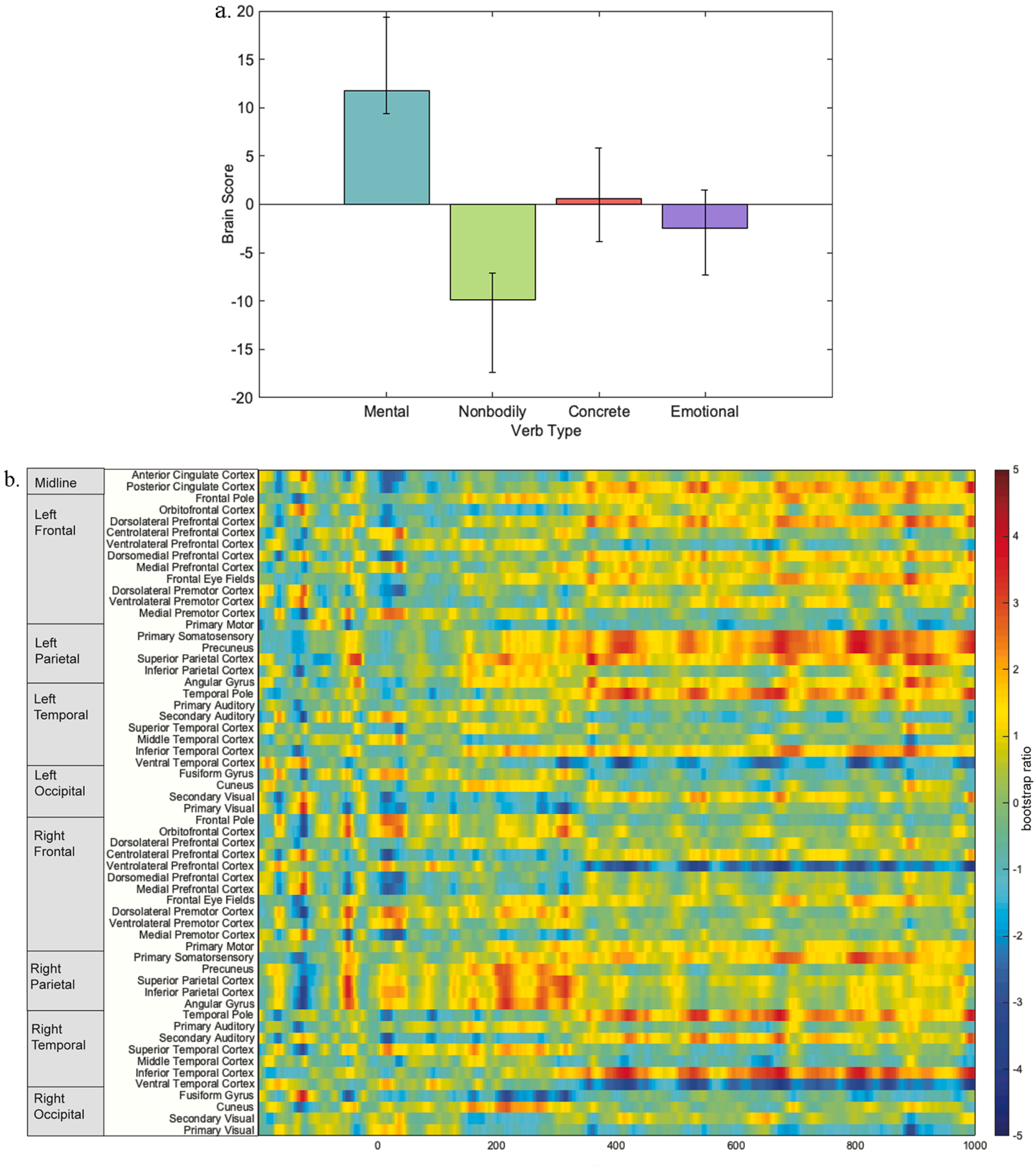

Fig. 6. a. Brain scores for each verb type indicate that, at ROIs and timepoints that are stable as indicated by bootstrap testing, mental state abstract verbs show more positive amplitudes compared to nonbodily state abstract verbs. Error bars represented 95% confidence intervals. b. Bootstrap ratio maps represent regions of interest and timepoints where differences between mental state and nonbodily state abstract verbs were most stable as determined by bootstrapping. Larger absolute bootstrap ratio values indicate more stable differences. Positive values indicate more active source estimates for mental state abstract verbs relative to nonbodily abstract verbs, and negative values indicate more active source estimates for nonbodily state abstract verbs relative to mental state abstract verbs.

linked to a sensorimotor, mental or emotional states of the body. This may enhance the ability to visualize the action, accounting for more positive source estimates in the ventral temporal lobe for nonbodily state abstract verbs. This is consistent with the conclusions of Harpaintner et al. (2018); (2020a;)), that abstract words with visual properties engage visual modalities during language processing. Indeed, the sustained time course of effects in the ventral temporal cortex is consistent with recent research which suggests that access to visual feature information during the processing of abstract words occurs at both early and late time points in conceptual processing (Harpaintner, Trumpp, & Kiefer, 2020b).

Alternatively, the observed activity in the ventral temporal cortex and fusiform gyrus may reflect a process of "crossmodal conjunctive representation" (Binder, 2016, p. 1101), as nonbodily state abstract verbs may have more associated concept activations than mental state abstract verbs. Furthermore, nonbodily state abstract verbs also showed more positive source estimates in the right ventromedial prefrontal cortex, another region which has been implicated as part of the semantic system that processes multimodal information (Binder et al., 2009; Binder, 2016; Kuhnke, Kiefer, & Hartwigsen, 2020). When evaluated alongside the differences observed in the primary somatosensory and precuneus regions, the results suggest that mental state abstract verbs are more reliant on introspective and tactile experience representations and nonbodily state abstract verbs may rely on more visual representations. Nonbodily state abstract verbs may also engage more multimodal associations, resulting in greater demands on regions associated with multimodal processing such as the ventral temporal cortex and the ventromedial prefrontal cortex.

Finally, although the PLS analysis on the source waveforms extracted from the discrete source analysis identified differences between nonbodily state abstract verbs and concrete verbs in the occipital cortex, these differences were not detected in the distributed source analysis estimates. We believe that the visual sources in the discrete source analysis accounted for variance that the distributed source analysis identified as present in the ventral temporal cortex, the fusiform gyrus and the cuneus. Given that the visual dipoles in the discrete source modeling were pre-set based on a visual task montage in the BESA software, it may be that subsequent dipoles in adjacent regions were not fit as they shared variance with the pre-set dipoles. This may have also influenced the resulting latent variables in the PLS analyses, as the differences in source estimates observed between mental state and nonbodily state abstract verbs in the distributed source analysis may not have been appropriately captured in the discrete source model waveforms.

There are some limitations to the current study. First, the number of available verb stimuli is small. Verbs are underrepresented in abstractness/concreteness, imageability, and BOI ratings studies relative to nouns, and when they are included in those ratings they are not distinguished from nouns; that is, the verb-specific meanings are not specified for ratings. The existing embodiment ratings, in contrast, do specify verb meanings but are only available for ~ 600 verbs. Additionally, the nonbodily state abstract verbs category was identified by low ratings on all semantic dimensions, rather than any key semantic dimension that could characterize those words. Future efforts to derive a greater range of lexical and semantic characteristics (including sensory-modality information) for more verb stimuli will allow researchers to study verb types that are more representative of different experiences, rather than groups dictated to some extent by availability of ratings. This may allow the effects of various modes of grounding to be more evident in the associated neural activity and provide adequate sample sizes to afford comparisons within verb types in order to assess similarity within these defined groupings. It has also been proposed that abstract words are more variable in nature (Borghi et al., 2017), showing more distributed networks of neural activation (Desai, Reilly, & van Dam, 2018). This inherent variability may make it difficult to discern between-group differences, as demonstrated by lack of clear differences or neural sources associated with emotional state abstract verbs. In future studies examining heterogeneity amongst abstract concepts, researchers may wish to address this by directly comparing brain signal variability between different abstract word groups.

In addition, using an active task that requires a motor response has the inherent challenge of avoiding movement artifacts in the time period of interest (~1,000 ms post stimulus presentation). Previous studies with go/no-go designs have shown evidence that suppressing a response has a distinct neural signature in a left-lateralized P3 component and is related to a decrease in activity in the inferior frontal gyrus, precentral gyrus and supplementary motor area (Smith et al., 2013). In our study, responses to all verb stimuli were withheld (rather than fully suppressed) for a 2,000 ms period so our assumption is that any effect due to the delayed response should be consistent across verb types. The accuracy rates for all verb types were high, indicating that no particular verb type was more or less difficult to judge. This would suggest that the effort required to withhold responses was also equal across verb types, otherwise we would expect to see differences in error rates. Nonetheless, this limitation must be considered and future research utilizing more passive tasks may be required to further evaluate the differences between abstract verb types seen here.

In sum, the ERP findings suggest that there is some heterogeneity amongst abstract verb types, with differences in ERP amplitude emerging between mental state and nonbodily state abstract verbs during a time course consistent with semantic processing. This further supports the view that a dichotomous concrete/abstract distinction masks important differences in neural activity underlying abstract verb types. The distributed source analysis revealed differences in neural generators for mental state and nonbodily state abstract verbs, suggesting that these verb types rely on distinct underlying representations. Furthermore, the contribution of heteromodal regions to the processing of nonbodily state abstract verbs and the contribution of both modal and amodal regions to the processing of mental state abstract verbs indicate that multiple sources of semantic information are likely combined during semantic processing. This supports hybrid, multimodal theories of semantic representation, which propose that concepts can be grounded in a number of sensorimotor, emotional, introspective, or linguistic experiences. For instance, it suggests that verbs that afford some kind of visual information (such as nonbodily state abstract verbs) engage with visual modalities during semantic processing to a greater extent than verbs which do not afford visual information (such as mental state abstract verbs). In contrast, mental state abstract verbs may engage tactile representations alongside introspective experience and are also associated with more source activity in typical linguistic regions of the temporal lobe. Overall, the present findings support the characterization of abstract words as comprised of heterogenous categories, grounded in a variety of model, introspective and linguistic experiences.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Verb Stimuli

Mental State Abstract	Emotional State Abstract	Nonbodily State Abstract	Concrete
accept	accuse	aid	adapt
add	annoy	align	announce
amend	betray	allow	awaken
aspire	beware	arrive	build
assert	cheat	ascend	chatter
assess	complain	assist	clothe
assure	condemn	attain	communicate
attempt	criticize	attend	crave
be	deceive	begin	defend
become	delay	broaden	devour
choose	demolish	cater	dine
coax	deprive	dissolve	discuss
compose	detain	ease	dive
decide	detest	embark	doze
devote	disappoint	enroll	evolve
excel	disobey	evaporate	exercise
find	envy	extend	exhale
foresee	evict	fasten	exist
improve	fail	keep	feel
invest	forbid	make	float
locate	hate	occur	focus
memorize	ignore	pause	glide
motivate	lose	pave	greet
obey	mislead	regain	ingest
ponder	mourn	renew	meditate
predict	offend	restore	munch
prove	owe	retire	pray
publish	pester	return	recover
realize	pry	send	seek
reflect	quit	share	sketch
reveal	reject	show	snooze
solve	reprimand	simmer	sprint
transform	resent	spend	taste
unite	shun	sweeten	visit
want	spoil	toughen	wander

Appendix B

Noun Stimuli

High BOI		Low BOI	
ale	medal	beaver	knack
ambulance	missile	beige	length
banner	moisture	berth	lightning
bay	mosquito	bliss	luck
birch	newt	breach	mauve
blob	pendulum	breadth	mode
brain	pint	brink	month
bureau	podium	brunt	night
cathedral	prison	chance	noon
certificate	projectile	creed	ode
chapel	rudder	dawn	peace
court	self	depth	plea
cub	shrine	deuce	prose
dame	silver	dinosaur	pun
den	skyscraper	dragon	rainbow
doctor	spa	drake	rhinoceros
dung	sport	dupe	scorpion
furnace	spud	elephant	south
gang	square	faith	speech
garage	stag	farce	squirrel
globe	temple	feat	stealth
grenade	thicket	fine	submarine
heart	thief	first	teal
highway	tomahawk	fond	theme
kelp	tomb	genie	third
king	tower	glad	trance
kit	trophy	gorilla	twelve
lobe	turpentine	guise	twinge
mantle	tweed	hertz	unicorn
mare	window	keen	volcano

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