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Semantic Richness, Concreteness, and Object Domain: An Electrophysiological Study

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Results from previous event-related potential (ERP) studies of semantic richness and concreteness effects have been mixed. Feature production norms have been used to derive one measure of semantic richness, the number of listed semantic features (NOF) for a given concept. Whereas some ERP studies have found evidence for a semantic richness continuum from abstract concepts, to concrete concepts with few features, to concrete concepts with several features, other studies have not. The present study assessed the effects of NOF (within concrete concepts) and concreteness (concrete vs. abstract concepts), on ERP amplitudes and behavioural decision latencies during a concrete/abstract decision task. It is important we also manipulated object domain, which has been found to influence ERP amplitude and topography. High and low NOF concepts were selected from animal and nonliving thing categories and all four conditions were matched on several potential confounds. We show that although decision latencies support a semantic richness continuum, electrophysiological activity does not. Whereas concrete concepts produce a larger negativity than abstract concepts, low NOF concepts are associated with larger negativities than high NOF concepts. We also replicate an increased posterior positivity for processing animal concepts, and report an interaction between object domain and semantic richness such that the NOF effect is larger within animal concepts.

Keywords: semantic richness, word recognition, concreteness, ERP, event-related potential

Humans possess the remarkable ability to comprehend the meanings of words in less than half a second. Electroencephalography (EEG) has been very useful for understanding how this occurs in real time, which is especially important for constraining models of word recognition and semantic memory organisation. In the current work we address the effects of semantic richness and object domain (animals and nonliving things) on brain activity accompanying single word reading. Specifically, we obtain event-related potentials (ERP) while participants perform a concreteness decision task on a set of concrete and abstract nouns. Our goal is to use our findings to inform current theories of semantic cognition and to extend the recent literature on semantic richness.

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Event-Related Potentials and Semantic Memory

The ERP technique, in which an average EEG signal across participants is computed relative to stimulus onset, is well suited for studying online meaning computation because it provides millisecond temporal precision and can be used to analyse small, fast-decaying neural signals invisible to functional magnetic resonance imaging (fMRI) and positron emission tomography (PET; e.g., Greenwald, Draine, & Abrams, 1996). One particularly relevant ERP component for the current study is the N400, which in part reflects a temporally dynamic interaction between the context in which a word occurs and the word's meaning (Kutas & Federmeier, 2000). The N400 time window may encompass at least two separable components. The classic N400 component introduced above is characterised by a central–parietal scalp distribution. In contrast, pictures (vs. words) and concrete words (vs. abstract words) have been shown to produce a more anterior N400-like component (Ganis, Kutas, & Sereno, 1996; Holcomb, Kounios, Anderson, & West, 1999; Kounios & Holcomb, 1994), which has been suggested to reflect activation of different cortical networks underlying concrete versus abstract knowledge. Specifically, Holcomb et al. (1999) suggest that the N400 should be divided into a posterior linguistically sensitive N400 that is sensitive to all word types, and a frontal imagistically sensitive N400 that is biased toward concrete nouns.

This more frontally distributed N400 effect has been used to study how different kinds of knowledge may be organized in the brain. The primary goal of this approach has been to determine whether computing the meanings of different types of stimuli is associated with separable temporal and/or spatial neurocognitive signals. Initial studies adopting this approach found that words referring to concrete objects produced a more negative and more anterior N400 than abstract words. This difference in scalp topography may reflect nonidentical neural generators; hence, the neural regions involved in processing these different kinds of concepts may be nonidentical, as supported by the fMRI literature (e.g., Martin, 2007). Holcomb et al. (1999) showed that the frontally distributed N400 is sensitive to concreteness, which supports Paivio's (1986) dual-coding theory, but that this concreteness effect can also be influenced by context, which supports the competing context-availability theory (Schwanenflugel & Shoben, 1983). However, the nonidentical scalp distributions underlying abstract and concrete word processing constitute evidence against the single store assumption of context availability theory. Holcomb and colleagues argue that their results are most consistent with dual-coding theory, which posits separate verbal and imagistic systems, and of importance, does not maintain that context cannot facilitate semantic processing.

In addition to differences between concrete and abstract concepts, more recent ERP studies have focused on differences within concrete object concepts, especially focusing on the living versus nonliving distinction (Kellenbach, Wijers, Hovius, Mulder, & Mulder, 2002; Kellenbach, Wijers, & Mulder, 2000; Kiefer, 2001, 2005; Paz–Caballero, Cuetos, & Dobarro, 2006; Sartori, Mameli, Polezzi, & Lombardi, 2006; Sim & Kiefer, 2005; Sitnikova, West, Kuperberg, & Holcomb, 2006), which first received attention in the context of category-specific semantic deficits—wherein knowledge about concepts from one domain (e.g., living things) is degraded relative to others (e.g., nonliving things; Warrington & Shallice, 1984). Several such ERP studies have found topographic effects of processing different knowledge types and/or object categories (Kiefer, 2001, 2005; Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008; Paz–Caballero et al., 2006; Sim & Kiefer, 2005; Sitnikova et al., 2006; but see Sartori et al., 2006). Generally, these studies found increased anterior negativity for living thing concepts relative to nonliving, and increased posterior negativity for nonliving thing concepts relative to living. These differences may reflect high-level visual processing in occipito-temporal cortex, and motor processing in frontal motor cortex (e.g., Kiefer, 2005; Sitnikova et al., 2006). Several fMRI/PET studies have demonstrated increased ventral posterior temporal activation (typically centered in fusiform gyrus) for highly imageable concrete words (Bedny & Thompson–Schill, 2006; D'Esposito, et al., 1997; Hauk, Davis, Kherif, & Pulvermüller, 2008; Sabsevitz, Medler, Seidenberg, & Binder, 2005; Wheatley, Weisberg, Beauchamp, & Martin, 2005; Wig, Grafton, Demos, & Kelley, 2005; Wise et al., 2000). Given that ventral temporal cortex, including the fusiform gyrus, appears central to processing visual form and colour information (Chao, Haxby, & Martin, 1999; Goldberg, Perfetti, & Schneider, 2006; Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; Simmons et al., 2007), the link between more imageable concrete words, and increased ventral temporal activation, can be taken to support the notion that concrete concepts contain richer visual representations than abstract concepts.

More frontal negativity for pictures versus words (e.g., Ganis et al., 1996; Federmeier & Kutas, 2001) and concrete versus abstract concepts (e.g., Holcomb et al., 1999; Kounios & Holcomb, 1994; West & Holcomb, 2000), as well as for living versus nonliving thing concepts as discussed above, provide converging evidence for the role of visual semantic knowledge in producing anterior N400 effects. Sitnikova et al. (2006) have suggested the common increased frontal negativity for concrete words, pictures, and living thing concepts, reflects activation of a visual feature system, since visual information may play a greater role in the representations of these stimuli in comparison with their respective controls. A main goal of the current study is to examine this idea of a continuum from the most abstract to the most concrete concepts in two object domains, by comparing ERP responses to abstract words and concrete words differing on number of verbally generated features.

Semantic Richness Effects on Brain and Behaviour

In recent years, a number of new semantic variables have been reported that have been shown to influence performance in tasks involving semantic memory use, including the extent to which features co-occur together across concepts (i.e., feature correlations; McRae, Cree, Westmacott, & de Sa, 1999), and the finding that features relatively unique to a concept tend to be computed faster than shared features (i.e., distinguishing features; Cree, McNorgan, & McRae, 2006; Randall, Moss, Rodd, Greer, & Tyler, 2004). Semantic richness has been among the most intensely studied constellation of variables. Although a precise definition of semantic richness has yet to be offered, a general definition is the amount of conceptual information that is associated with a single concept. An initial finding based on computational modelling suggested that concepts with richer representations settle more quickly into stable patterns of activation (Plaut & Shallice, 1993). An empirically derived measure of semantic richness, namely number of features, has been particularly well studied. A main finding, now called the number-of-features (NOF) effect, is that concepts consisting of several semantic features are responded to faster than those consisting of fewer features (e.g., Grondin, Lupker, & McRae, 2009; Pexman, Holyk, & Monfils, 2003; Pexman, Lupker, & Hino, 2002; Pexman, Hargreaves, Siakaluk, Bodner, & Pope, 2008). The NOF effect may be related to the concreteness effect in that concrete words are responded to more quickly than abstract words in various semantic and lexical tasks (e.g., Binder, Westbury, McKiernan, Possing, & Medler, 2005; Strain, Patterson, & Seidenberg, 1995). Plaut and Shallice (1993), for instance, suggested that this effect reflects the relatively richer semantic representations for concrete versus abstract words. Pexman, Hargreaves, Edwards, Henry, and Goodyear used fMRI to examine the effects of semantic richness (2007a) and concreteness (2007b) on brain activity. They showed that words with greater semantic richness produced less activation than words with less semantic richness in several brain regions, and that concrete words produced less widespread neural activation than abstract words.

These modelling, behavioural, and fMRI findings have been important in increasing our understanding of the relationship between semantic richness, brain, and behaviour. Electrophysiology, however, is uniquely suited to increase our knowledge of how semantic richness influences brain activity in real time. To our knowledge, only three previous studies have directly addressed the effects of semantic richness on the electrophysiological activity underlying word meaning computation.

Kounios et al. (2009) asked participants to perform semantic relatedness judgments on word pairs, and derived ERPs timelocked to the onset of the first word. They found no amplitude differences between high number of feature concepts and abstract concepts, but found that low number of feature concepts generated increased N400 amplitude versus abstract concepts. This result is not consistent with a monotonic continuum of neural activity associated with processing concepts that are abstract, low richness, and high richness concepts, respectively. The authors concluded that previous studies may have confounded concreteness with semantic richness, and suggested future studies should explicitly account for both kinds of variables.

Rabovsky, Sommer, and Abdel Rahman (2012) derived ERPs to word onset in a lexical task, and in contrast to Kounios et al. (2009), found that words with many semantic features generated larger N400 amplitudes at centro-parietal sites than words with fewer features. Similarly, in a multivariate analysis, Amsel (2011) found words with greater numbers of semantic features generated increased negativity starting around 300 ms poststimulus onset. Unlike Kounios et al. (2009), these two results are consistent with previously reported N400 concreteness effects (Kounios & Holcomb, 1994; West & Holcomb, 2000). The ERP concreteness effect, however, may reflect a more complex relationship between word meaning and brain activity than previously thought. In a novel test of the concreteness effect, Huang, Lee, and Federmeier (2010) manipulated the concreteness of adjectives describing polysemous nouns while holding the nouns constant, and assessed concreteness effects independently in both hemispheres. When words were processed by the right hemisphere, a sustained concreteness effect occurred after about 450 ms at frontal sites consistent with previously reported imagery-mediated effects (West & Holcomb, 2000), whereas the same stimuli processed by the left hemisphere led to a reduced N400 for concrete versus abstract modifying adjectives, consistent with greater contextual support of concrete items.

Despite significant progress, it is clear that inconsistencies remain in this literature. Taken as a whole, these reviewed findings suggest that the relationship between semantic richness and electrophysiological activity is quite complex, and requires further study. In addition to our attempt to pin down the relationship between ERP amplitude and amount of semantic richness, we will examine if object domain plays a role in the expression of semantic richness in electrophysiological activity.

Overview of the Current Study

This study extends the literature in two main respects. Of importance, we match conditions on several important lexical and semantic variables known to affect behavioural and/or ERP responses, some of which may have affected results in previous functional neuroimaging and behavioural studies. Using this stimulus set, we can test the possibility that amount of semantic information drives the frontally distributed N400 concreteness effect. We also plan to compare our results with the handful of recent ERP studies of semantic richness effects, which thus far have produced conflicting results.

In addition, by contrasting high NOF concepts with low NOF concepts in two object domains, we can examine whether semantic richness effects depend on object domain, and test the possibility that the increased frontal N400 negativity for living versus nonliving things is due to increased activation of semantic features (e.g., Sitnikova et al., 2006). If the frontal N400 indexes amount of semantic visual information and abstract concepts contain less visual information than concrete concepts, then the order of frontal N400 amplitude, from high to low, should be high NOF, then low NOF, then abstract concepts. However, if the frontal N400 does not index this dimension, we would predict no amplitude differences between high and low NOF concepts, but that abstract concepts would still generate the smallest N400.

Behavioural Study

We first report a separate concrete/abstract decision experiment with the items to be used in the ERP study. Participants judged, as quickly and accurately as possible, whether each of 192 words referred to a concrete or abstract concept. Of the 96 concrete words, 48 referred to animals, and 48 to nonliving things. Number of features (NOF) and object domain were manipulated in a factorial design, and several important variables were matched as closely as possible across conditions. We conducted an independent behavioural experiment for two reasons. First, these data can be interpreted in terms of the word recognition literature, which provides an empirical base from which to understand the electrophysiological data. Second, these data enable a comparison between the immediate neural response and the resultant behavioural decision. Participants in the ERP study delayed their concrete/abstract decisions until after the critical EEG recording period to minimise motor artifacts. Based on previous studies (Pexman et al., 2002, 2003, 2008), we predicted processing advantages for high versus low NOF concepts. In addition, because we controlled for semantic structure variables known to influence lexical and semantic task performance, we predict no differences in decision latencies across domains.

Method

Participants. Twenty-two undergraduate students (age range: 18–24 years; 14 female; three left-handed) participated for course credit at the University of Toronto Scarborough (UTSC). All participants had normal (or corrected) vision and had spoken English as a first language for 10 or more years.

Materials. Experimental stimuli were 192 English words. Ninety-six concrete words were selected from among norms from McRae, Cree, Seidenberg, and McNorgan, 2005, and 96 abstract words (48 nouns, 48 adjectives) to be used as fillers were selected from the Medical Research Council Psycholinguistic database (Coltheart, 1981). Abstract words had concreteness values less than 350 (mean [M] = 272; standard deviation [SD] = 33.6). Concrete words were all object nouns. Abstract and concrete words were matched on important psycholinguistic variables (see Table 1).

Concrete words were 48 living and 48 nonliving thing concepts. Each category was divided into 24 high and 24 low NOF groups, creating a 2(NOF: high, low) $\times$ 2(domain: animal, nonliving thing) within-subjects factorial design (see Table 2). Although the majority of previous studies have not further fractionated the living thing domain, important differences exist between different kinds of living things (e.g., animals vs. fruits & vegetables: Cree & McRae, 2003; Vinson, Vigliocco, Cappa, & Siri, 2003). We therefore selected only animal concepts. Nonliving concepts belonged to several categories according to McRae et al. (2005): automobile,

Table 1
Variables Measured on Concrete and Abstract Words (N = 192)

Variable	Concrete mean (*SD*)	Abstract mean (*SD*)	*t* value	*p*
Letters	6.11 (2.1)	6.01 (1.8)	.37	.71
Syllables	1.86 (.8)	2.03 (.7)	−1.49	.14
Phonemes	5.03 (1.6)	5.25 (1.7)	−.93	.35
Orthographic neighbors	4.13 (5.9)	3.49 (5.5)	.76	.45
Phonological neighbors	8.36 (11.5)	7.69 (12.8)	.38	.70
Familiarity	4.57 (1.73)	4.56 (.8)	.06	.95
Word frequency	7.45 (1.6)	7.74 (1.5)	−1.25	.21
Imageability	574 (61)	362 (65)	—	—

clothing, gun, house, musical instrument, shelter, tool, utensil, vehicle, and weapon.

The NOF measure was derived from the McRae et al. feature production norms by summing the number of features listed for each concept (excluding taxonomic features). This measure was used to divide concepts into high and low NOF conditions, within both animal and nonliving thing concepts. The NOF did not statistically differ by domain, nor did it significantly interact with domain. Several variables were matched as closely as possible between all four concrete word conditions (i.e., across object domain and NOF), and are motivated as follows. Previous ERP research has shown that phonological and orthographic word characteristics readily affect the ERP signal (Bentin, Mouchetant–Rostaing, Giard, Echallier, & Pernier, 1999; Hauk, Pulvermüller, Ford, Marslen–Wilson, & Davis, 2009; Laszlo & Federmeier, 2011). We therefore attempted to match number of orthographic and phonological neighbors across conditions. We also matched number of syllables, phonemes, and letters.

Word frequency has also been shown to affect ERP amplitude (Hauk, Davis, Ford, Pulvermüller, & Marslen–Wilson, 2006; Hauk, Pulvermüller et al., 2009), and behavioural task performance (Yap & Balota, 2009), and was matched across conditions. McRae et al. (2005) asked participants to rate from 1–9 how familiar they were “with the thing to which the word refers.” This measure of concept familiarity was matched across conditions. Typicality has been extensively shown to affect verification latencies (e.g., Casey, 1992; Larochelle & Pineau, 1994), thus, typicality ratings made available from O’Connor, Cree, and McRae (2009) were matched.

Recent work suggests correlational structure plays an important role in word meaning computation, which compels either direct manipulation or control of these variables. We matched two such measures available in McRae et al. (2005). Intercorrelational density indexes the degree of feature-feature correlation among all features within a concept, and has been shown to predict reaction time in speeded lexico-semantic tasks (McRae et al., 1997), and feature distinctiveness indexes the degree to which a concept’s feature-based representation consists of distinctive (i.e., non-shared) features, and has been shown to affect speeded task performance (Cree et al., 2006; Randall et al., 2004). All matched and manipulated variables are shown in Table 2. Finally, although we could not obtain values for concreteness and imageability for every item from currently existing databases (see Table 2 for percent-

Table 2
Matched and Manipulated Variables Within Concrete Words (N = 96)

Variable	Nonliving		Animal	
	Low NOF	High NOF	Low NOF	High NOF
Syllables	1.9 (0.8)	2.0 (0.9)	1.7 (0.6)	1.9 (0.9)
Letters	6.2 (2.2)	6.6 (2.3)	5.7 (1.7)	5.9 (2.3)
Phonemes	5.3 (1.7)	5.3 (1.8)	4.6 (1.4)	5.0 (1.6)
Orthographic neighbors	3.6 (4.6)	4.5 (7.0)	4.0 (6.5)	4.4 (5.6)
Phonological neighbors	7.3 (8.5)	11.5 (16.0)	7.5 (11.0)	7.1 (9.1)
Word frequency	7.3 (1.6)	7.7 (1.9)	7.2 (1.3)	7.6 (1.6)
Familiarity	4.6 (1.9)	5.0 (2.0)	4.1 (1.1)	4.6 (1.6)
Typicality	6.3 (1.6)	6.6 (1.5)	6.4 (1.4)	6.9 (1.3)
Density	111.4 (176.3)	179.4 (156.6)	183.3 (182.9)	202.8 (142.8)
Distinctiveness	0.31 (0.17)	0.30 (0.13)	0.30 (0.2)	0.25 (0.1)
Concreteness[a]	603 (43)	617 (31)	614 (40)	636 (25)
Imageability[b]	575 (47)	588 (40)	537 (78)	594 (58)
NOF	9.3 (2.8)	13.4 (2.4)	10.0 (2.8)	13.5 (2.2)
% Visual	41	59	42	61
% Other sensory	13	5	11	7
% Function	27	22	15	10
% Encyclopedic	19	13	31	22

Note. NOF = number of features; Visual = visual motion, color, and parts and surface; Other sensory = smell, taste, sound, tactile.
[a] 20 of the 96 items did not have values on this measure. [b] 37 of the 96 items did not have values on this measure.

ages), these variables were matched as closely as possible across conditions given their known influence on word recognition.

Procedure. Participants performed an abstract/concrete decision task individually in a dimly lit room. The experiment was implemented with E-Prime (Psychology Software Tools, Inc) on a personal computer, using a PST serial response box (Psychology Software Tools, Inc.). They were seated approximately 60 cm from the monitor, on which characters subtended approximately 1×0.8 degrees of visual angle in height and width respectively. Each session began with 12 practice trials (six concrete; six abstract words not used in the experiment). Following practice, participants completed one block consisting of all 192 words. Word presentation order was randomized. Each trial consisted of a fixation point ("+") presented in the centre of the screen for 1,000 ms, which was replaced with the word for 500 ms. Participants had 2,500 ms in which to respond using a PST serial response box. The intertrial interval following the response window was 1,000 ms. Participants were instructed to signal concrete words with the index finger of their dominant hand, and abstract words with the index finger of the other hand. They were instructed as follows: "Concrete words denote objects. That is, things that can be perceived by your senses; you could feel, hear, see, smell, or taste these objects." Although this arrangement could amplify a concrete word latency advantage, we were principally interested in differences within concrete word conditions, and wanted participants to signal these responses with their dominant hand.

Results

One participant's data were removed from analyses due to excessive errors (<75% accuracy). Trials resulting in errors were excluded from latency analyses. Trials above 3 *SD*s from the grand mean verification latency and below 200 ms were replaced by these respective values, affecting less than 2% of trials. Verification latencies were analysed with linear mixed models incorporating crossed random effects of subjects and items, which have been shown to reduce the probability of committing Type I and II errors (Baayen, Davidson, & Bates, 2008). The denominator degrees of freedom used to test the fixed effects in mixed effects models do not have exact *F* distributions. Therefore the Satterthwaite approximation of denominator degrees of freedom was used (the default in SPSS mixed procedure), which is intended to produce a more accurate *F* test approximation.

In temporal order, participants responded fastest to high NOF animal ($M = 645$, standard error [SE] $= 35$), high NOF nonliving thing ($M = 698$, $SE = 35$), low NOF animal ($M = 706$, $SE = 35$), and low NOF nonliving thing ($M = 712$, $SE = 35$) items. We found a main effect of domain, $F(1, 78) = 4.0$, $p = .05$ and a main effect of NOF, $F(1, 78) = 6.4$, $p = .01$, but the interaction term was not statistically significant, $F(1, 77) = 2.4$, $p = .12$. Specifically, participants were faster to respond to animal versus nonliving thing concepts, and high versus low NOF concepts.

Discussion

The processing advantage for high versus low NOF concepts is consistent with Pexman et al. (2003, Exp. 2a), who found NOF significantly predicted latencies in an abstract/concrete decision task across living and nonliving items. The processing advantage for living versus nonliving thing concepts in the current study is somewhat unexpected given the control of both lexical and conceptual variables across domains, but has been found in previous behavioural studies (e.g., Pilgrim, Moss, & Tyler, 2005).

In sum, behavioural results indicate expected effects of high versus low NOF words, consistent with a facilitative role of semantic richness. We now present the ERP experiment using the identical item set, the results of which suggest a more complex relationship between behavioural and electrophysiological markers of the role of semantic richness, and domain, in word meaning computation.

ERP Study

Method

Participants. Twenty-three undergraduate students (age range: 17–24 years; 15 females) at UTSC participated for course credit or monetary compensation. Participants had normal (or corrected) vision and no visible or verbally reported neurological or psychiatric impairments. Inclusion criteria included right-handedness, and >10 years speaking English.

Materials. The items were identical to Experiment 1.

Procedure. Participants were tested individually in a dimly lit sound-proof room using E-Prime software (Psychology Software Tools) on a PC linked to a Sony cathode ray tube monitor with refresh rate 60 Hz. Each trial consisted of a fixation ("+") for 1,500 ms, followed by a target word for 750 ms, followed by a white screen for 1,250 ms, followed by the response cue "Respond now," which remained on the screen for a random duration between 1,500 and 2,495 ms. Stimulus presentation duration was changed to 750 ms to preclude possible effects of stimulus offset during the recording epoch. Characters were presented in size 18 black Tahoma Bold font against a white background in the middle of the screen; participants sat at a viewing distance of about 90 cm. They were seated approximately 90 cm from the monitor, on which characters subtended approximately 0.7×0.5 degrees of visual angle in height and width respectively. Participants were instructed to categorise each word as concrete or abstract by pressing the right or left mouse button, respectively, once they saw the response cue. Responses were delayed until after word presentation to minimise overt motor effects on the EEG. Participants were allowed a break after every 25 trials.

ERP recording parameters. Scalp potentials were collected across 64 sintered Ag/AgCl electrodes mounted in an elastic cap utilizing the international 10–5 electrode system (Waveguard, ANT), and electrode AFz served as ground. The EEG was recorded and then stored offline with ASA software (ANT). The EEG was referenced offline to the average of the left and right mastoids, which were equated at 5 kΩ during recording. All other electrode impedances were kept below 5 kΩ. Eye movements were monitored with supra and infraorbital electrodes. The EEG was amplified with an ANT high-density amplifier (22 bit, 71.5 nV/bit) at a sampling frequency of 512 Hz. The data were bandpass filtered offline between 0.1 and 100 Hz. The EEG was segmented into epochs corresponding to 100-ms prestimulus onset until 700-ms poststimulus onset, and corrected to a 100-ms baseline prestimulus onset.

Data analysis. Data from three participants contained excessive artifacts and were removed. Eye movement artifacts including blinks were automatically detected at EOG sites using a 30-μV standard deviation threshold in a 200-ms sliding window, and marked for removal. Only artifact-free EEG segments containing correct trials entered into analyses. Based on visual inspection of the waveforms and previous studies, we selected two time windows corresponding to the N400 (300–500 ms) and a late semantic window (500–700 ms). Repeated measures analyses of variance (ANOVAs) were performed on mean, rather than peak voltages (Luck, 2005), and the Greenhouse–Geisser correction was used to correct degrees of freedom if sphericity was violated (from herein we report uncorrected degrees of freedom, but corrected F and p values).

Concrete words were divided into a 2 (domain) × 2 (NOF) factorial ANOVA. Analyses were conducted for each time window (300–500, 500–700 ms). An omnibus ANOVA was conducted with one additional factor, site (62 electrodes). To examine hemisphere and laterality effects, three additional analyses were conducted on three parasagittal electrode arrays located along a posterior–anterior axis (midline, medial, lateral). An additional factor of hemisphere (left, right) was entered into medial and lateral analyses. Midline analyses had eight electrode levels (FPz, Fz, FCz, Cz, CPz, Pz, POz, Oz). Medial analyses had 14 electrode levels (FP1/2, AF3/4, F1/2, F3/4, FC1/2, FC3/4, C1/2, C3/4, CP1/2, CP3/4, P1/2, P3/4, PO3/4, O1/2). Lateral analyses had 13 electrode levels (AF7/8, F5/6, F7/8, FT7/8, FC5/6, T7/8, C5/6, TP7/8, CP5/6, P5/6, P7/8, PO5/6, PO7/8).

Results

Visual inspection of waveforms revealed typical early components including a posterior P1/N1 complex with peaks at about 140 and 180 ms. All but distal posterior sites produced a component resembling P2 peaking between 180 and 220 ms. Although we did not plan to perform analyses on this component, post hoc ANOVA analyses did not reveal any amplitude differences between conditions. A clearly delineated negative-going potential with an anterior maximum was generated at all but posterior sites beginning around 280 ms, and peaking between 370 and 420 ms. Finally, a late positivity peaked around 600 ms at central and posterior sites. Table 3 reports significant main effects and interactions for all analyses presented below. We found no effects of hemisphere in any analysis, nor did peak latency differ across any comparisons.

Comparisons Within Concrete Concepts

N400 window (300 to 500 ms). A negative-going component peaking around 400 ms is clearly visible in all conditions at frontal sites (see Figure 1). Inspection of scalp maps divided by domain and NOF (Figure 2; left column) reveals that this negativity is frontally distributed for all concrete words. Although the main effect of NOF did not reach conventional significance values (.05 < p's < .10), low NOF words generated a larger negativity than high NOF words across central and frontal sites (see Figure 1). There was no main effect of domain, but domain interacted with electrode site in all but lateral ANOVAs such that central/posterior sites were less positive for nonliving things than for living things. Interestingly, a domain by NOF interaction was found at midline sites, and to a lesser extent medial sites, such that the amplitude difference between high and low NOF concepts was significantly greater in the animal versus nonliving thing items (see Figure 2; left column).

Late window (500 to 700 ms). Between 500 and 700 ms, the scalp topography was dominated by a central–posterior positivity, and residual negativity at anterior sites (see Figure 2). We found main effects of domain in all models such that nonliving words were more negative than living thing words; this effect was broadly distributed, as evidenced by the lack of any interaction with electrode site. As was visible in the previous epoch, an unexpected main effect of NOF was found in all analyses such that low NOF words generated a larger negativity than high NOF words. Similar to the main effect of domain, the NOF effect was broadly distributed and did not interact with electrode site. Finally, we found no significant interaction between domain and NOF.

Comparisons Between Concrete and Abstract Concepts

We elected to perform one additional analysis incorporating ERPs to the abstract words (matched on lexical variables with the concrete words), for the main purpose of comparing these results with those of Kounios et al., 2009, who found a peculiar pattern of ERP amplitudes to abstract, low number of feature, and high number of feature concepts. Comparing the mean amplitudes of conditions based on unequal numbers of trials should be approached with caution; however, mean amplitude measures pro-

Table 3
F Values of Main Effects and Interactions in ERP Amplitudes

	300–500 ms				500–700 ms			
	All	Midline	Medial	Lateral	All	Midline	Medial	Lateral
Concrete words								
Domain	1.1 (1, 19)	1.1 (1, 19)	1.0 (1, 19)	1.1 (1, 19)	**8.5****	**10.6****	**9.5****	**5.8***
Domain × Site	**3.6**** (61, 1159)	**5.6**** (7, 133)	**5.4**** (13, 247)	2.8 (12, 228)	1.2	1.4	0.8	1.3
NOF	3.4 (1, 19)	3.8 (1, 19)	3.5 (1, 19)	2.5 (1, 19)	**11.0****	**10.7****	**11.2****	**8.0***
NOF × Domain	3.0 (1, 19)	**4.5*** (1, 19)	3.5 (1, 19)	1.8 (1, 19)	0.1	2.1	0.3	0.1
All words								
Word	**7.1**** (4, 19)	**7.8**** (4, 19)	**6.4**** (4, 19)	**6.1**** (4, 19)	**7.2****	**8.2****	**7.8****	**5.3****
Word × Site	**2.7**** (244, 4636)	**6.8**** (28, 532)	**5.4**** (52, 988)	**2.4*** (48, 912)	1.4	1.5	1.4	0.8

Note. Table 3 contains F values for main effects and interactions in repeated-measures ANOVA models of by-subject ERP amplitudes in two time windows. Uncorrected degrees of freedom are shown for all terms in all models in the first time window; degrees of freedom are identical for all terms in all models in the second time window, and are not shown. Concrete words refers to the models fitted to the data from the concrete nouns and all words refers to the models fitted to the entire item set including the abstract words. Bold entries correspond to statistically significant terms in the ANOVA model.
* $p < .05$. ** $p < .01$.

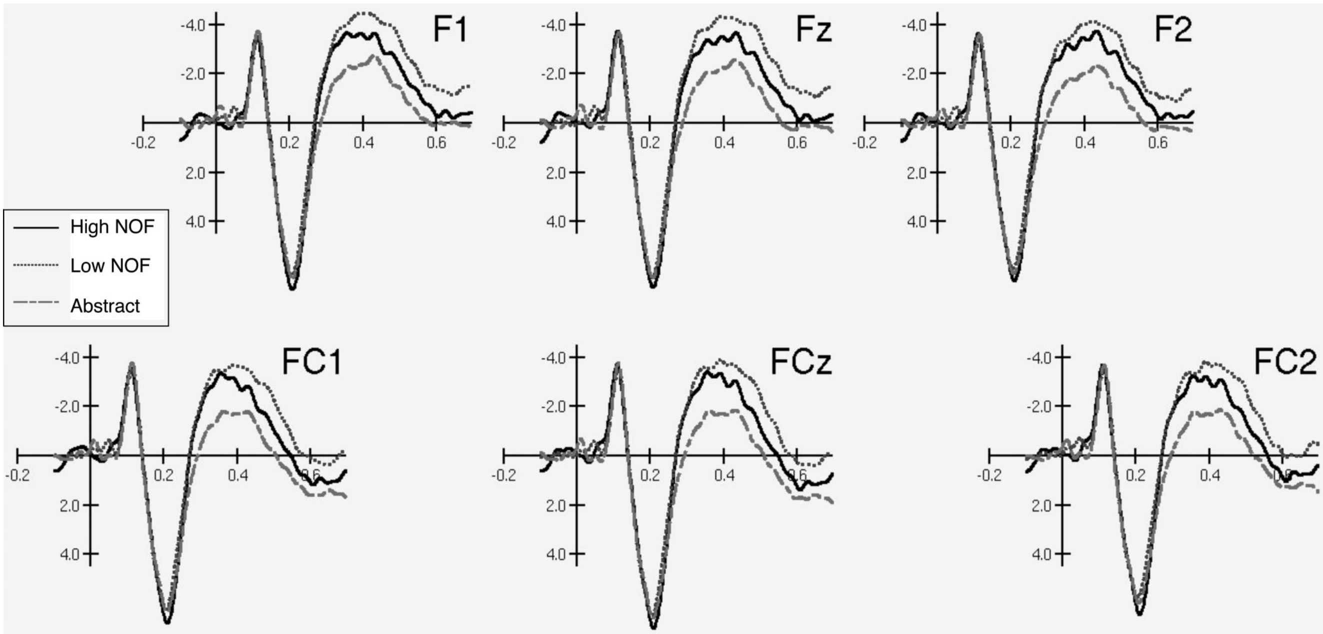

Figure 1. Grand averaged ERPs for abstract words and low/high NOF concrete words at representative central/frontal electrode sites. The larger negativity for both concrete conditions versus abstract words is visible at all sites, along with the larger negativity for low versus high NOF concepts. The abstract ERPs also appear to diverge from the concrete ERPs earlier than the two concrete word ERPs.

duce reasonably constant means and effect sizes as number of trials increase, and the within-concrete word trials were composed of a relatively large amount of trials. The following one-way repeated-measures ANOVAs contain five levels according to word type: abstract, high/low NOF animals, and high/low NOF nonliving things. Topographic factors were identical to those described above. Given the direct comparisons within concrete concepts above, we conducted planned comparisons between abstract words and each of the four concrete word conditions.

Between 300 and 500 ms, main effects of word type and word type by electrode interactions were significant in all ANOVAs. Planned comparisons revealed that abstract words were significantly less negative than all other conditions (p's $< .01$) at central and frontal sites, but that at posterior sites abstract concepts were equivalent to high NOF animal concepts. This pattern of results can be seen in the first column of Figure 3. A significant main effect of word type was found in all analyses in the 500- to 700-ms epoch such that abstract words were significantly less negative than all concrete conditions (p's $< .01$), with the exception of living thing high NOF words, which did not differ from abstract words (second column of Figure 2). Unlike the previous epoch, no interactions were found.

Discussion

Participants performed a concrete/abstract decision task on a set of 96 abstract and 96 concrete words. Concrete words were divided into four equal matched conditions, enabling a direct test of how semantic richness affects the electrophysiological brain activity accompanying the computation of concepts within and across animal and nonliving thing categories. As we will see, consideration of our findings as well as previous ERP results precludes a straightforward interpretation of the relationship between electrophysiological activity and semantic richness.

ERPs, Concreteness, and Semantic Richness

We found an unexpected pair of results given the direction of the previously reported ERP concreteness effect. All word types produced a negative-going component resembling the N400 (albeit with a more anterior scalp distribution). This component was less negative for abstract words than concrete words, replicating previous work. On the other hand, low NOF concepts were associated with a larger negative-going component than high NOF concepts beginning around 300 ms and lasting for several hundred milliseconds.

These results suggest that levels of semantic richness within concrete concepts and levels of concreteness across all kinds of concepts cannot be combined into a single spectrum of conceptual information—at least in terms of the intensity of evoked brain activity. The discrepant concreteness and NOF effects were surprising in part because in contrast, the behavioural results paired with the standard behavioural concreteness effect did suggest a single continuum of semantic richness. That is, the standard behavioural concreteness effect (concrete concepts are responded to more quickly than abstract concepts; see Paivio, 1991, for review) was extended to a within-concrete word comparison (i.e., number of semantic features). If the neural mechanism that underlies behavioural processing advantages for highly imageable concrete words, versus less imageable concrete and abstract words is driven by quantity of semantic information, the N400 amplitude captured in the present study does not appear to reflect this mechanism.

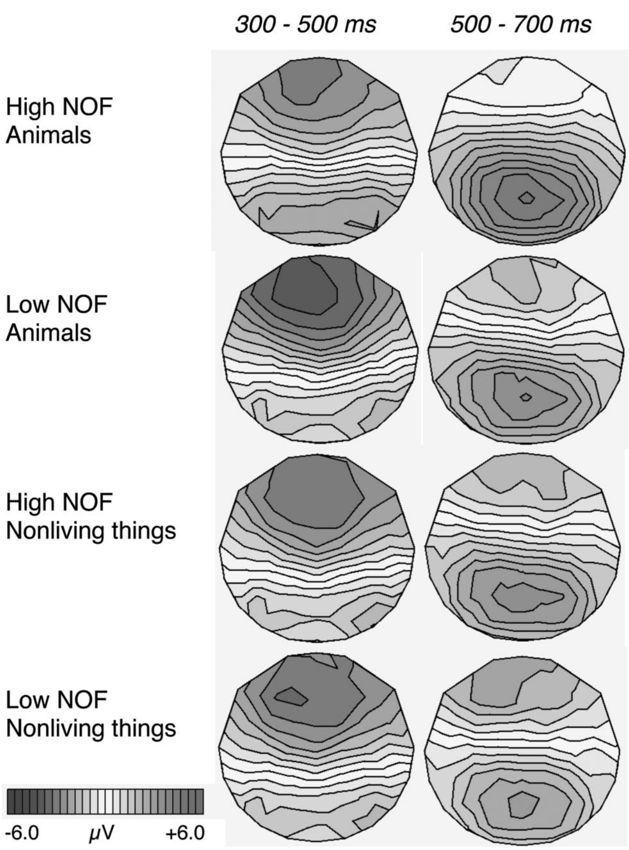

Figure 2. Two-dimensional interpolated voltage distributions of each concrete word condition averaged within two time windows of 200-ms duration. The top of each map indicates the front of the head. The central/frontal distribution of the negative potential (N400) is clearly visible in the 300 to 500 ms time window, and the more posterior distribution of the late positivity is most visible in the 500- to 700-ms time window.

One explanation of the unexpected direction of the NOF effect is that the abstract/concrete decision task biased participants to expect either unambiguously concrete or abstract words, in which case low NOF words did not fit easily into the context of abstract/concrete decisions, and were more difficult to process. A puzzling discrepancy exists between behavioural performance and ERP amplitude, however, which cannot be resolved by solely considering difficulty of processing. Behavioural evidence suggests a monotonic relationship between quantity of semantic information and speed of processing, in that concrete words are responded to faster than abstract words, and concrete concepts with many features are responded to faster than those with few features (Grondin et al., 2009; Pexman et al., 2002, 2003, 2008). Conversely, the present ERP study demonstrated that N400 and late (500–700 ms) component amplitudes are largest for concrete words with few features, followed by concrete words with many features, whereas the standard ERP concreteness effect is such that concrete words generate a larger N400 than abstract words (Holcomb et al., 1999; Kounios & Holcomb, 1994; West & Holcomb, 2000). The difficulty of processing explanation seems even less likely considering Kounios et al. (2009) used semantic relatedness judgments, which would not bias participants to expect unambiguously abstract or concrete concepts. Additional possibilities arise when considering the previous ERP studies on the NOF effect.

The present NOF effect is in the opposite direction of two previous ERP studies (Amsel, 2011; Rabovsky et al., 2012), but in the same direction as Kounios et al. (2009). There are several differences between these four studies, including four different tasks, different item sets matched on overlapping but nonidentical potential confounding variables, and two different offline voltage reference transformations. Can task requirements account for the current split in the reported direction of NOF effect? The Amsel (2011) and Rabovsky et al. (2012) studies employed delayed imagery judgments and speeded lexical decisions, respectively, and the current study and Kounios et al. (2009) employed concreteness judgments and semantic relatedness judgments, respectively. One potential division is the relatively explicit semantic demands in the latter two studies. Judging whether a word refers to an object that is or is not perceivable with the senses clearly requires semantic access, as does judging whether two objects are related. In contrast, lexical decision does not logically require semantic access, and imagery judgments are designed to reflect the ease with which a word's referent comes to mind rather than some property of the object itself.

Another potential difference between ERP studies of the NOF effect is the relative number of features of concepts in each item set. The low and high NOF conditions in the present study had on average 9.7 and 13.5 features, respectively. In the Amsel (2011) item set, which contained a range of NOF items for use in regression analyses, the mean number of features was 12.8 and the 25th and 75th percentiles were 11 and 15, respectively. Kounios et al.'s (2009) low and high NOF conditions had an average of 9 and 15.7 listed features. Therefore it does not appear that differences between NOF conditions can account for the discrepancy in results.

It is important to note that the effect sizes in these four studies are generally no larger than 1 μV, which is quite small in comparison with, for example, the classic N400 semantic expectancy effect of at least 4 μV. Given these effect sizes, one next step in resolving the above discrepancy will be to utilize an item set consisting of only the very highest and lowest NOF concepts, while matching on all known confounds. That said, small effects are not necessarily less interesting effects. In light of the current discrepancy in NOF ERP studies, we believe additional studies should address the extent to which the direction of the effect depends on task requirements. For example Amsel (2011) found that NOF effects of specific kinds of features (e.g., visual motion vs. function) were in opposite directions, which suggests that a total NOF effect may depend in part on the degree that the task emphasised certain kinds of knowledge and also the relative numbers of different kinds of features in a given item set.

A general implication of these results is that highly concrete, less concrete, and abstract concept representations vary along multiple dimensions not yet understood (including object domain; see next section), and these dimensions may interact to produce unexpected patterns of behavioural and neurophysiological data. The collection of verbally generated features of abstract concepts divided into knowledge types including introspective, social, emotional, event, and different sensory modalities (for preliminary results see Wiemer–Hastings & Xu, 2005) would be useful to determine whether abstract concepts fall into the lower region of a

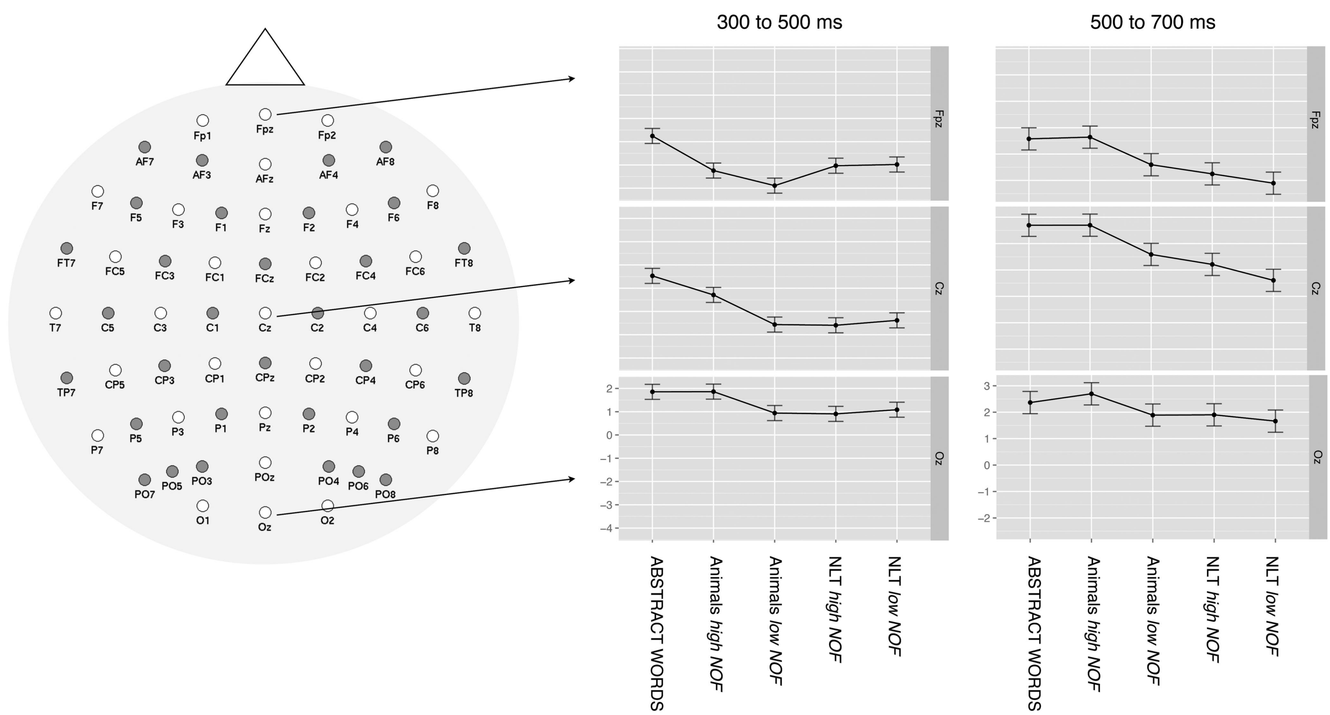

Figure 3. Mean amplitudes (across participants) for every experimental condition and their 95% confidence intervals are plotted for two time windows at three midline electrode sites corresponding to frontal (Fpz), central (Cz), and posterior (Oz) positions. The y-axis is consistent within columns (time windows). In the N400 time window, the decreased negativity for abstract words versus all concrete conditions is visible at central/frontal sites, whereas the posterior site reveals equivalent voltages for abstract and high NOF animal concepts. In addition the interaction between domain and NOF is visible at all sites such that the NOF difference is largely driven by the animal concepts.

NOF distribution as was assumed in the Plaut and Shallice (1993) simulations, or whether these variables reflect largely independent aspects of conceptual representation. In addition, although feature norms are one of the best available methods of specifying conceptual content, they clearly have limitations. Certain types of content may be under reported, such as the colour intensity, visual texture, or presence of highly frequent properties (e.g., has a heart, is large). It will be important to carry out experiments designed to tease apart the contributions of not only semantic richness and concreteness, but other recently reported measures of conceptual content. For instance, object attribute ratings provide a continuous measure of several sensory and nonsensory properties, some of which are underrepresented in feature norm studies. Amsel, Urbach, and Kutas (2012) recently collected a large set of such attribute ratings and showed that certain kinds of knowledge (especially those kinds that are underrepresented in feature counts like smell and taste knowledge) can account for unique variance in semantic and lexical decision latencies, over and above commensurate NOF measures. Modality-exclusivity ratings (e.g., Lynott & Connell, 2009; van Dantzig, Cowell, Zeelenberg, & Pecher, 2011) capture the extent to which a given property is perceived through a single sensory modality (e.g., "red") versus multiple modalities (e.g., "fresh"). One could factorially manipulate number of features and modality exclusivity to tease apart the influences of each. Finally, body-object interaction ratings (BOI; Bennett, Burnett, Siakaluk, & Pexman, 2011; Tillotson, Siakaluk, & Pexman, 2008) index the extent to which a person interacts with an object using any part of his body, and high BOI words are responded to more quickly in lexical and semantic decision tasks after controlling for imageability and concreteness (Siakaluk, Pexman, Aguilera, Owen, & Sears, 2008; Siakaluk, Pexman, Sears, Wilson, Locheed, & Owen, 2008).

ERPs and Object Domain

We reported two category-related ERP effects in the current study. One, we replicated several previous ERP studies that have used both words and pictures and several different tasks, by showing that words denoting living things are associated with larger positive amplitudes in the N400 time window at posterior and central electrodes, than words denoting nonliving things (Kiefer, 2001, 2005; Sim & Kiefer, 2005). Two, and more important for the present work, we found a category by NOF interaction of N400 amplitude at midline sites such that the NOF effect was significantly larger for animal versus nonliving thing items.

Kiefer and colleagues have suggested that the increased positivity to living thing concepts near the back of the scalp is consistent with sensory/motor property models of semantic memory organisation (Martin, 2007), which would predict that computing the meaning of words denoting living versus nonliving thing concepts would rely more on visual representations stored in posterior temporal cortex. The domain by NOF interaction could also reflect a unique role of visual knowledge. According to a measure of visual complexity derived from visual feature counts (Cree & McRae, 2003; McRae et al., 2005), visual information is more salient in the representations of living things (and especially animals) versus nonliving things. Visual motion features in particular are known to be extremely salient in the representations of animal concepts (Cree & McRae, 2003), and the number of visual motion features has been found to exert a strong influence on ERP amplitude (Amsel, 2011). Successfully distinguishing between different animals is assumed to rely more on visual information than differentiating between nonliving things, which is consistent with the larger effect of NOF in animal concepts. Although the task did not require basic-level differentiation, some proportion of visual information may be computed automatically following perception of the word form, which could account for a differential effect of NOF across domains.

A related possible cause of the interaction between object domain and NOF involves differential recruitment of multiple kinds of modality-specific knowledge. Perhaps the representations of the high NOF animal concepts were relatively reliant on visual information, which resulted in relatively effortless concreteness judgments, whereas additional types of sensory (smell, taste, sound, tactile) and nonsensory (function, encyclopedic) knowledge were recruited to judge the low NOF animal concepts as concrete, leading to a larger N400. Inspection of the proportion of different feature types in Table 2, however, suggests the proportions of different kinds of knowledge were quite similar across object domains. In particular, the proportion of visual features in the low versus high NOF conditions was almost identical for both kinds of objects.

The present category-related effects along with previous ERP studies that contrasted different object categories may also be consistent with some degree of domain specificity, in addition to modality specificity. Mahon and Caramazza's (2009) distributed domain-specific hypothesis, unlike certain modular accounts of domain specificity, shares the assumption of the sensory/motor property models that different kinds of knowledge (e.g., visual motion, colour) are represented in different neural circuits. They also maintain, however, that certain object domains with evolutionarily important histories (e.g., animals, tools) are innately specified independent of experience. Our data do not constitute direct evidence for or against this hypothesis, but one possibility is that both principles of organisation acted in concert to produce the domain by NOF interaction.

In addition to the principles of semantic memory organisation introduced above, another not mutually exclusive principle is correlational structure. Differences in intercorrelational density between animal and nonliving concepts may have contributed to the increased posterior positivity for animal concepts, as well as the domain by NOF interaction. According to the conceptual structure account (e.g., Tyler & Moss, 2001), the distinctive features of nonliving things are more highly correlated than the distinctive features of animal concepts, and animal concepts are composed of a larger proportion of shared features, which should lead to measurable differences in behavioural and neural measures of computation. However, animal and nonliving thing concepts did not differ on concept distinctiveness or number of distinctive features in the current items, which suggests our category-related effects are not due to differences in these measures of semantic structure. That said, although intercorrelational density was matched as well as possible (no statistical difference existed between item types), the nonliving things (M = 145) were somewhat lower than the animals (M = 193) on this measure. To further explore this aspect of our items we computed a different kind semantic density measure from the co-occurrence statistics derivable from large text corpora provide. We computed a co-occurrence based measure of semantic density using the correlated occurrence analogue to lexical semantics (COALS; Rohde, Gonnerman, & Plaut, 2004)—a global word co-occurrence model that improves upon the influential hyperspace analogue to language model (HAL; Lund & Burgess, 1996). Specifically, we computed the mean distance between each word in our item set and its 10 nearest neighbors among the 500,000 most common words in the text corpus COALS is based on, and computed the mean of this measure for each condition. A one-way ANOVA revealed that the mean semantic density among the nonliving thing items (M = .47, SD = .41) was significantly higher than among the animal items (M = .41, SD = .10), which is the opposite of the typical feature-based living thing advantage in density, including the slight advantage present in this item set. Given the opposite average values of semantic density for the living and nonliving thing items according to feature-based versus co-occurrence-based measures, we cannot draw any strong conclusions about the relationship between semantic feature density and ERP amplitude in this experiment.

Finally, our category-related effects could reflect the specificity of the level at which concepts are activated (i.e., the degree to which a concept must be differentiated from near semantic neighbors). Although there is no obvious reason to suspect that the concreteness task led participants to activate living and nonliving thing concepts at different levels of specificity, it is the case that some apparent category-specific effects are sensitive to level of specificity (e.g., Dixon, Bub, & Arguin, 1997; Lambon Ralph, Lowe, & Rogers, 2007; Rogers & Patterson, 2007). Category-specific effects observed when participants classify objects at the basic level can disappear when the same concepts are classified at a more specific level (Rogers & Patterson, 2007). Similarly, herpes simplex encephalitis patients have been shown to exhibit category-specific deficits in naming at a general level, but not when both animals and nonliving things need to be discriminated from their semantic neighbors (Lambon Ralph, et al., 2007). Level of specificity has also been shown to influence the time course of object recognition. Clarke, Taylor, and Tyler (2011) found that domain-level naming generated earlier category-related neural activity than did basic-level naming. Future ERP studies are needed to determine the extent to which the NOF effect differs across object domains when the task demands different levels of differentiation, and to what extent this relationship occurs in a consistent time window.

The interaction between object domain and semantic richness is intriguing. The current data cannot definitively adjudicate between the possibilities suggested above, but we provided a handful of testable predictions and offered some potential explanations. We think future studies will need to control for the level of specificity in which concepts are retrieved, the salience of sensory information demanded by the task, and statistical feature-based information before we will fully understand how semantic richness and the other discussed measures of conceptual structure interact with object domain during language comprehension.

Résumé

Les résultats d'études antérieures sur le potentiel évoqué (PE) des effets de la richesse sémantique et de la concrétude sont variés. Les normes d'établissement des caractéristiques ont servi à définir une mesure de la richesse sémantique, le nombre de caractéristiques sémantiques (NCS) pour un concept donné. Certaines études portant sur le PE ont trouvé des preuves d'un continuum de la richesse sémantique, allant de concepts abstraits jusqu'à des concepts concrets dotés de peu de caractéristiques, puis à des concepts aux nombreuses caractéristiques; toutefois, d'autres études n'en ont pas trouvé. La présente étude évalue les effets du NCS (dans des concepts concrets) ainsi que de la concrétude (concepts concrets *vs* concepts abstraits), sur l'amplitude du PE et du temps de latence des décisions comportementales durant une tâche de décisions concret - abstrait. Le domaine des objets a été manipulé, ce qui a influé à la fois sur l'amplitude du PE et sur la distribution topographique. Des concepts au NCS réduit et élevé ont été choisis parmi des catégories d'animaux et des catégories d'objets inanimés; il y a eu correspondance entre les quatre conditions quant à plusieurs facteurs confusionnels. L'étude révèle que le temps de latence des décisions appuie la notion d'un continuum de la richesse sémantique, contrairement à l'activité électrophysiologique. Les concepts concrets sont associés à une plus grande négativité que les concepts abstraits, tandis que les concepts au NCS réduit sont associés à une plus grande négativité que les concepts au NCS élevé. Les auteurs ont aussi fait une réplique d'une positivité postérieure accrue pour le traitement des concepts d'animaux et rapportent une interaction entre le domaine des objets et la richesse sémantique, de sorte que l'effet du NCS est plus grand pour les concepts d'animaux.

Mots-clés : richesse sémantique, reconnaissance des mots, concrétude, PE, potentiel évoqué.

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