How the mass counts: An electrophysiological approach to the processing of lexical features

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Nouns may refer to countable objects such as tables, or to mass entities such as rice. The mass/count distinction has been discussed in terms of both semantic and syntactic features encoded in the mental lexicon. Here we show that event-related potentials (ERPs) can reflect the processing of such lexical features, even in the absence of any feature-related violations. We demonstrate that count (vs mass) nouns elicit a frontal negativity which is independent of the N400 marker for conceptual-semantic processing, but resembles anterior negativities related to grammatical processing. This finding suggests that the brain differentiates between count and mass nouns primarily on a syntactic basis. *NeuroReport* 12:999–1005 © 2001 Lippincott Williams & Wilkins.

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INTRODUCTION

Lexical features are word properties that are assumed to specify each lexical entry on a variety of linguistic dimensions, such as syntactic and semantic information. Syntactic features determine a given word's major grammatical category, such as noun, verb or preposition, and specify more fine-grained syntactic information within each category. Thus syntactic features are important for both meaning-bearing content words (nouns, verbs, adjectives, etc.) and grammatical function words (articles, auxiliaries, conjunctions, etc.). In contrast, semantic features distinguish content word categories, such as nouns referring either to animate or inanimate objects. That is, semantic features represent linguistic word information which corresponds to (or is based on) conceptually relevant distinctions. Although lexical features play an important role in linguistic theory, reports on neuro-physiological correlates of word category differences are rare. Most empirical knowledge about the neural basis of features encoded in the mental lexicon rests on observations of patients with greater impairments for certain word categories than for others. Such dissociations have been observed for both semantic features [1] and syntactic categories [2].

In linguistic as well as psycholinguistic research, the distinction between count and mass nouns has attracted some attention due to its relevance to syntax and its links to conceptual semantics. It is widely agreed that the mass/count distinction is at least partly syntactically based, as it affects syntactic distribution. However, it is controversial whether the underlying feature information is primarily semantic [3–5] or syntactic [6,7] in nature. Similar considerations apply to lexical features such as gender (masculine/feminine/neuter). Neuro-linguistic research may shed light on this question, as the processing of the conceptual-semantic and the syntactic domains has been argued to involve distinct brain mechanisms [8].

Grammatical approaches to the mass/count distinction emphasize morpho-syntactic differences [6,7]. Unlike count nouns (e.g. car and table), mass nouns (e.g. rice and furniture) cannot be pluralized. The two noun types also have different grammatical requirements with respect to determiners (e.g. much rice but many tables; there is rice but there is a table). Syntax-related approaches are supported by considerable cross-linguistic variability in the categorization of words as count or mass, which would not be expected if the mass/count distinction primarily reflected universal conceptual differences. Thus the English word hair is a mass noun, the corresponding Italian word capelli is a (plural) count noun, and in German both a mass and a count noun co-exist (Haar *vs* Haare). Languages like Chinese or Thai do not show the mass/count distinction at all but use mass-like nouns plus a system of classifier morphemes for countable entities (a unit of table (ness)) [3,9]. If English count nouns, and Chinese mass nouns plus classifiers, refer to similar concepts, it is tempting to treat the mass/count distinction as a purely syntactic phenomenon.

Proponents of a semantic mass/count distinction emphasize the underlying conceptual basis, observed already in young pre-linguistic infants, which seems to play a crucial role during the acquisition of mass/count differences [10,11]. Infants conceptually distinguish between non-solid substances (identified by their material but not their shape) and solid objects (identified by shape but not material); the former serve as prototypes for mass nouns, the latter for count nouns [10,11]. The noun properties of languages like Thai or Chinese seem to suggest that mass nouns are semantically basic, and that the meaning of count nouns is derived from them [3]. Even for the less typical and therefore more problematic cases of super-ordinate mass nouns such as furniture, empirical data suggest conceptual-semantic differences as compared to count super-ordinates (e.g. chairs) [5]. Within the theoretical linguistic framework of Conceptual Semantics, the mass/count phenomenon is explained by means of conceptual features [4] (or semantic primitives).

To our knowledge, the present study is the first report on the use of event-related brain potentials (ERPs) to examine the psychological and neural processes underlying the mass/count distinction. Previously, ERPs have been employed to elucidate the time course and other aspects of language processing, in both the semantic [12–14] and syntactic [14–16] domains. The best-studied language-related component is the N400, a centro-parietal negativity peaking around 400 ms whose amplitude seems to reflect differences in conceptual-semantic processing [12]. The N400 amplitude increases if semantic integration becomes difficult, such as in cases of semantic feature violations (e.g., the animacy violation in 'the marmalade was murdered') [13]. In contrast, syntactic processing difficulties are reflected by a left anterior negativity (LAN) [14–16] and a late parietal positivity, the P600 (or syntactic positive shift) [12,14,16]. LAN components have been observed for syntactic feature violations such as word category violations [14,15] and syntactic agreement errors [13,16]. Like the large majority of psycholinguistic ERP investigations, all studies cited here employed the violation paradigm in which incorrect (or unexpected) words are compared to appropriately used control words. The rationale behind this paradigm is that a particular kind of linguistic violation is hypothesized to require additional processing within the violated domain (i.e. syntactic violations requiring extra syntactic processing, etc.) [12,14]. However, the observed ERP components may reflect the detection and repair of these violations, rather than any operations typical for normal language processing. It is therefore important that the N400 and the P600 components have also been observed for more subtle processing differences, without employing the violation paradigm [12].

A largely unresolved question is to what extent the processing of linguistic features associated with lexical entries can also be investigated in ERP studies of normal language processing. Thus grammatical gender has only been examined using the violation paradigm, which has yielded a (syntactic) P600 rather than a (semantic) N400 [16,17]. Most lexical access studies of normal (non-violation) processing have focused on the comparison of two broad classes of vocabulary types, namely the closed class of grammatical function words and the open class of meaning-bearing content words [18–20]. They have reported larger N400s for content words and an ensemble of enhanced (left) anterior negativities between 150 and 700 ms for grammatical function words. Early anterior negativities between 150 and 350 ms (referred to as the N280 or the lexical processing negativity) have been interpreted as reflections of the earliest processing differences among syntactic word categories [18–20]. This notion was challenged by two studies demonstrating that the observed function/content word ERP differences are at least partly due to frequency and word length effects [21,22]. Nevertheless, even these ERP studies acknowledge that the frontal components are independent from the semantic N400. The subsequent and more consistent frontal negativity between 350 and 700 ms for function words (referred to as N400–700 or N350–550) has been tentatively interpreted in terms of a contingent negative variation (CNV) reflecting the expectation of the subsequent word being either, on one view, a meaning-bearing content word, or alternatively the head of a grammatical constituent [20]. Taken as a whole, the processing of grammatical lexical features might be reflected by frontal ERP components such as the N280, the N350-550, or the LAN, and conceptual-semantic aspects by the more posterior N400. Their topographical differences should thus allow distinguishing between competing semantic and syntactic accounts of lexical features such as in gender or in the mass/count distinction.

This idea was pursued in the present study. Because isolated words may be processed in a somewhat unnatural manner, the critical nouns were embedded in sentence structures. In order to hold constant the context in which mass and count nouns are processed, the critical words were preceded by a possessive modifier compatible with both noun types (e.g. John's information, or Martha's explanation). That is, syntactic differences between count and mass nouns were not emphasized. A recent behavioral study had demonstrated that the mass/count distinction is being processed even if not required by the context [23]. In order to rule out any expectancy-related processes [20], all target nouns were followed by prepositional phrases (see Table 1), such that expectations concerning subsequent words were the same for count and mass nouns. To rule out any confounds caused by known frequency and word length ERP effects in the relevant time interval [21,22], these factors were matched across mass and count nouns. Finally, in contrast to previous ERP studies of lexical features [16,17], no violations of the critical feature itself (such as in many rice(s), or much table(s)) were employed.

However, the sentences did include semantic plausibility violations that were expected to elicit prototypical posterior N400 effects (see Table 1). In addition, comparisons between function and content words were performed in order to yield a prototypical anterior negativity. These prototypical components (i.e. N400 and anterior negativity, respectively), measured in the same subjects, served as templates for characterizing the expected mass/count effect. Depending on whether the mass/count effect re-

Table 1. Sentence examples for each of the four main conditions. Target words of the ERP analyses are underlined.

Condition	Example
1a Plausible count	Yesterday, I translated Diane's story for the children
1b Plausible mass	The detective shared Linda's information with the attorney
2a Implausible count	The hiker put Kathleen's glacier on the floor
2b Implausible mass	Yesterday, I donated Carmen's fog to the orphans

sembled either the N400 or the anterior negativity, we could infer whether the mass/count distinction is primarily semantic or syntactic. A semantic mass/count distinction would be expected to yield an N400, which, according to previous research [24], would be expected to interact with the semantic plausibility N400. A syntactic feature effect, by contrast, should pattern with the frontal negativity.

MATERIALS AND METHODS

Twenty-six male undergraduate students from the University of Oregon, all right-handed with no left-handers in their immediate families, and without neurological disorders, participated in the study after giving informed consent. They were seated in a dimly illuminated, shielded chamber and read a total of 96 critical sentences (plus 160 filler sentences, 96 of which contained syntactic violations) in a pseudo-randomized order. Half of the critical sentences (conditions 1a and 2a in Table 1) contained count nouns and half mass nouns (conditions 1b and 2b) that either made sense (1a, 1b) or were semantically implausible (2a, 2b) in the sentential context. Sentence versions (plausible/implausible) were balanced across subjects, with each subject seeing only one version of each sentence. Sentences were presented word-by-word on a computer monitor (300 ms per word plus an inter-stimulus interval of 200 ms); 1500 ms after the end of each sentence, subjects judged its acceptability (good or bad?) by pressing either the yes or no button on a response box. Response hand was counterbalanced across subjects. Count and mass nouns were matched with respect to frequency and word length. For the grammatical word class analyses contrasting content and function words, items were selected only if they either occurred in correct sentences or preceded violations. Scalp EEG was recorded continuously from 27 cap-mounted electrodes with a 250 Hz sampling rate (impedances $< 2\,k\Omega$), referenced to the right mastoid and re-referenced off-line to averaged left and right mastoids. EOG was acquired bi-polarly between electrodes placed at the outer canthi of the eyes, and from mastoid-referenced electrodes placed above and below the orbit. After automatic EEG and EOG artifact rejection, 1200 ms epochs were computed for critical nouns in each main condition, as well as for content and function words, using a pre-stimulus baseline of 100 ms. Subject average waveforms in each condition were low-pass filtered at 60 Hz. Amplitude comparisons in a time window between 300 and 600 ms after stimulus onset were statistically analyzed with ANOVAs for repeated-measures, separately for the midline (three electrode levels FZ, CZ, PZ) and for lateral electrodes (with additional factor hemisphere (2)). At lateral sites, each region of interest (ROI) comprised 4 electrodes (e.g., left anterior: FP1, F3, F7, FT7; left central: FC5, C3, C5, CT5; left posterior: P3, T5, TO1, O1). Analyses of the plausibility N400 and the mass/count effect were performed on the same target nouns and included factors plausibility (2) $\times$ mass/count (2) $\times$ electrode site/ROI (3). As the comparisons between content/function words and mass/count effects necessarily included ERPs of different target words, corresponding ANOVAs required a different design that virtually contrasted difference waves (see Results). Additionally, more fine-grained analyses were performed in five successive 100 ms time windows between 200 and 700 ms. Where appropriate, Huynh and Feldt corrections and a modified Bonferroni correction were applied in order to protect against progressive Type I errors.

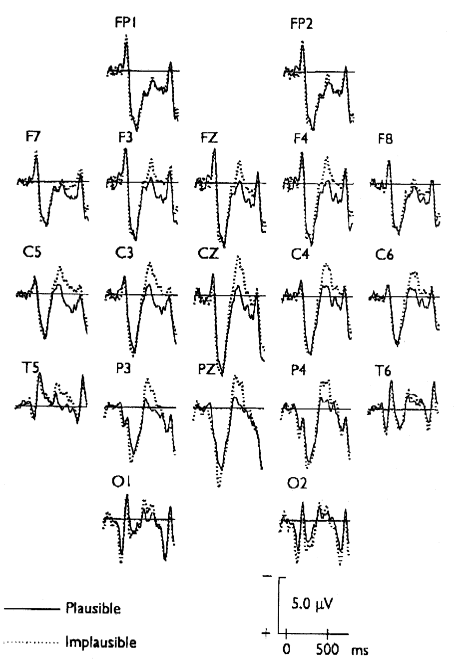

Fig. 1. ERPs of the plausibility effect at 19 electrodes (conditions 1a+1b vs 2a+2b). The vertical line at 0 ms marks the onset of the target noun. The typical N400 effect between 300 and 600 ms for the implausible nouns (dotted line) is most prominent at centro-parietal electrodes. Negative amplitudes are plotted upwards in all figures.

RESULTS

Behavioral data: Subjects performed almost perfectly in the judgment task (mean 93% correct), with no significant differences across conditions.

ERPs: Figure 1 shows the ERP main effect of semantic plausibility over both count and mass nouns. As expected, nouns that were implausible in the sentential context elicited a broadly distributed classical N400 component with a centro-parietal maximum. As summarized in Table 2, the plausibility main effect was highly reliable in the time window between 300 and 600 ms at both midline and lateral electrodes. It did not interact significantly with the anterior/posterior dimension, but independent analyses indicated that it was most prominent at central and posterior areas (Table 2). In contrast, the mass/count distinction (Fig. 2a,b) was reflected by a different, more frontal ERP component. This negativity had a significantly different topographical distribution than the N400 and was confined to frontal electrodes only (Table 2). Importantly, it proved to be functionally completely independent of the N400 plausibility effect. That is, the interaction plausibility × mass/count did not reach significance ($F < 1$; see Table 2 and Fig. 2a,b), thus indicating purely additive effects. Neither plausibility nor mass/count effects were found in the early time window between 200 and 300 ms ($F < 1$).The mass/count comparison within plausible sentences (conditions 1a *vs* 1b in Table 1) is displayed in Fig. 2a. Count nouns elicited a larger frontal negativity than mass nouns between 300 and 600 ms. The corresponding effect within implausible sentences (i.e. conditions 2a *vs* 2b) is shown in Fig. 2b.

Figure 3 illustrates the comparison between content and function words. Replicating previous findings [18,20–22], function words elicited two anterior negativities as compared to content words: one at 200–300 ms (in the time range of the P200) and one at 300–600 ms. The earlier effect (lateral: $F(1,25) = 49.28$; $p < 0.0001$; midline: $p < 0.0001$) is probably due to frequency and word length differences [21,22]. This effect did not occur during the plausibility and mass/count contrasts, as these factors were controlled for among those target nouns. The early negativity was bilateral (word class × hemisphere: F1), whereas the later negativity was most prominent over left frontal electrodes.

A direct comparison of the later grammatical word class effect and the mass/count effect (in the 300–600 ms time window) revealed interesting similarities. We virtually contrasted ERP difference waves: that is, the late frontal negativity for function words (function words minus content words; see Fig. 3) against the negativity for count nouns (count nouns minus mass nouns; Fig. 2a,b). The anterior negativity for function words between 300 and 600 ms displayed the same anterior maximum as the mass/count effect. The global ANOVAs revealed a main effect of negativity (lateral: $F(1,25) = 8.75$; $p < 0.001$; midline: $p < 0.002$), indicating that both the mass/count and word class negativities were significant. There was a negativity × electrode/ROI interaction (lateral: $F(2,50) = 27.32$; $p < 0.0001$; midline: $p < 0.02$) indicating a common frontal maximum, whereas no interaction with factor condition (word class negativity *vs* mass/count negativity) was found ($F < 1$). (Note: due to the frontal word class effect being larger than the frontal mass/count effect, a three-way negativity × condition × electrode interaction

Table 2. Statistical effects for factors plausibility and mass/count in the time range 300–600 ms after noun onset.

Analysis (300–600 ms)	Source	F-value (dF = 1,25)[a]	p-value
Midline electrodes	Plausibility	17.76	0.0003
	Plausibility × Electrode	1.96	n.s.
	Mass count	3.87	0.06
	Mass count × Electrode	2.55	0.1
	Plausibility × Mass count	1.42	n.s.
	Plausibility × Mc × electrode	0.33	n.s.
FZ	Plausibility	6.03	0.03
	Mass count	6.36	0.03
CZ	Plausibility	21.93	0.0001
	Mass count	2.70	n.s.
PZ	Plausibility	15.03	0.001
	Mass count	1.74	n.s.
Lateral electrodes	Plausibility	22.56	0.0001
	Plausibility × ROI	1.44	n.s.
	Mass count	3.56	0.07
	Mass count × ROI	5.35	0.02
	Plausibility × Mass count	0.80	n.s.
	Plausibility × Mc × ROI	1.04	n.s.
Frontal	Plausibility	5.04	0.06
	Mass count	8.01	0.01
Central	Plausibility	29.33	0.0001
	Mass count	4.22	0.07
Posterior	Plausibility	10.36	0.006
	Mass count	0.85	n.s.

[a]Degrees of freedom (dF) are 2,50 for effects with factor electrode/ROI.

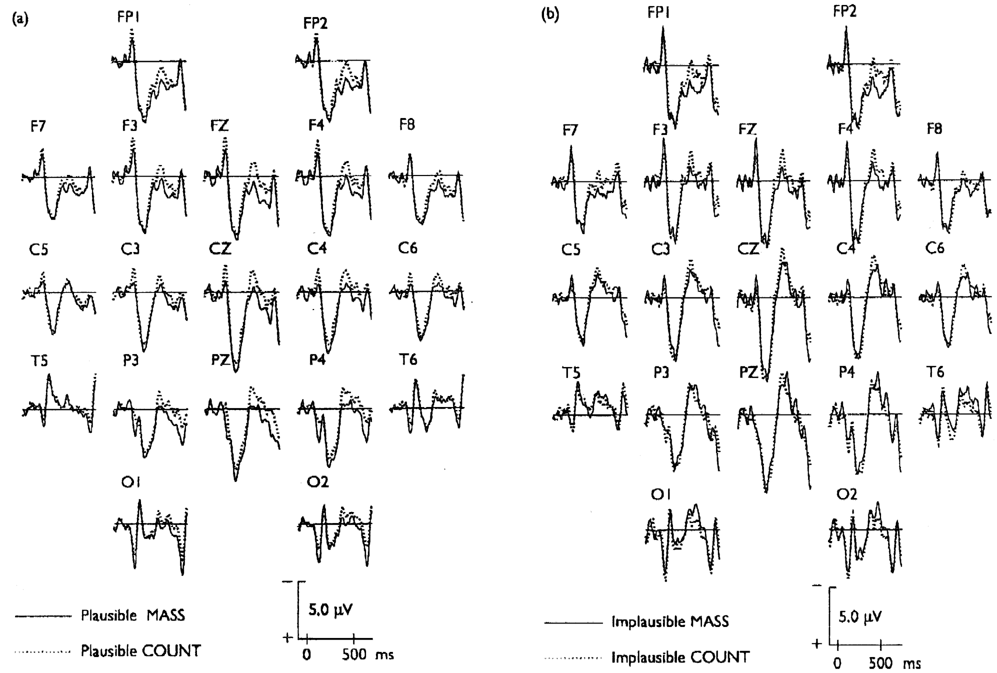

Fig. 2. (a) ERPs of the mass/count effect within plausible sentences (condition 1a vs 1b). Count nouns (dotted line) elicit a more negative potential than mass nouns (solid line) between 300 and 600 ms. Unlike the N400 effect in Fig. 1, this mass/count effect is most prominent at anterior electrodes, with a slight preponderance in the left hemisphere. (b) ERPs of the mass/count effect within implausible sentences (condition 2a vs 2b). The frontal mass/count effect (i.e. a more negative potential for count nouns; dotted line) is also observed in implausible sentences, indicating its independence of the nouns' plausibility.

($p < 0.03$) was obtained for the original data. However, this interaction disappeared completely after a standard data normalization procedure [25] ($F < 1$), indicating a pseudo-effect resulting from the inappropriate linear model underlying analyses of variance [25].) The only reliable topographic difference between the two components was a clear left hemispheric preponderance for the word class effect but not for the mass/count effect (negativity × conditions × hemisphere: $F(1,25) = 4.39$; $p < 0.04$. However, as previous reading studies had shown that lateralization effects of syntax-related negativities can occur most reliably at F7 and F8 electrodes [26], we performed a *post-hoc* analysis at these electrodes. The analyses revealed a significant mass/count effect at F7 in the left hemisphere ($p < 0.03$) but not at its right-hemispheric homologue F8 ($p > 0.3$), indicating a tendency of left-lateralization for the mass/count effect.

DISCUSSION

First, our data show that the processing of lexical features can be successfully monitored with ERPs, even without employing the widely used violation paradigm. The finding of a robust mass/count effect confirms assumptions of linguistic theories with respect to the general relevance of such features in mental lexicon.

Second, it was demonstrated that the mass/count effect's topographical profile resembled that of the anterior negative components linked to grammatical processing, rather than the more posterior N400 component regularly observed for conceptual-semantic processing. This result points to a grammatical distinction in the brain, thus favoring syntactic [6,7] over semantic [3–5] accounts as the primary basis of the mass/count distinction. In a broader context, it demonstrates a new on-line approach for the study of even the normal (i.e. non-violation) processing of lexical features.

Third, unlike word class effects, the present frontal mass/count effect cannot be attributed to different expectations concerning subsequent words. It thus challenges previous interpretations of the late anterior negativities found for function *vs* content words [20]. That is, even the late frontal components between 350 and 700 ms may be more directly linked to grammatical processing than has been assumed. Our findings may also partly explain the frontal negativity that has been reported for concrete *vs* abstract words [27] (but see [28]). In that study, the concrete noun example (table) was a count noun, and the

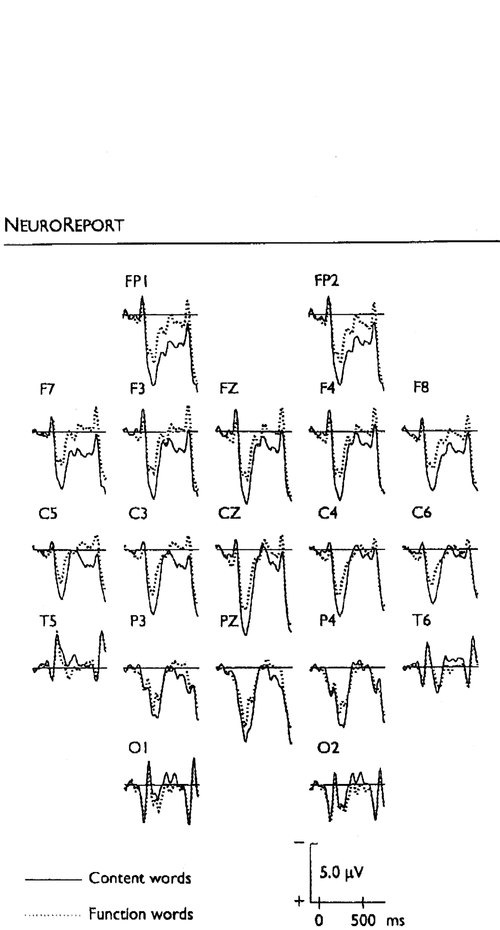

Fig. 3. ERPs of the word class effects. The comparison of content words (solid line) and function words (dotted line) replicates previous findings of anterior negativities for the function words (see main text). The early negativity between 200 and 300 ms is probably due to frequency and word length differences. The subsequent left anterior negativity between 300 and 600 ms resembles that of the mass/count effect.

abstract noun (justice) was a mass noun, suggesting a potential confound of concreteness and the mass/count feature. Note however, that the frontal concreteness effect was clearly right-lateralized, suggesting a distinct effect from the present mass/count component, which displayed a tendency of left-lateralization.

Fourth, the frontal mass/count ERP effect was found in approximately the same time window as the posterior N400 plausibility effects. This observation seems to confirm current views [14,26] suggesting that semantic integration and the activation of syntactic information in the lexicon take place roughly in parallel.

A final issue concerns the polarity of the mass/count effect. As mass nouns, but not count nouns, appear to exist in all natural languages [3,9], they could be viewed as the default value, or unmarked case, whereas count nouns may represent the marked case. In psycholinguistics, marked forms are assumed to require additional processing. Thus the frontal effect might be interpreted as a relative negativity for count nouns. However, a different interpretation is possible: a relative positive going waveform for mass nouns. One behavioral study [23] reported longer processing times for mass nouns, as would be expected if count nouns are the unmarked case. As ERP components are usually defined as difference waves between two conditions, not as deflections in one single condition, the polarity of the shift depends on which condition is viewed as the baseline. In most cases, a given component is interpreted as a reflection of additional processing costs. Following this line of thinking, mass nouns would elicit a more positive-going wave than count nouns by virtue of their requiring additional processing resources.

These questions point to the necessity of further investigation into the electrophysiology of the mass/count distinction. The present study, being the first of its kind, cannot establish definitively the direction of the effect. Nevertheless, the observation of a robust frontal ERP effect for the mass/count distinction, in highly controlled normal processing conditions, is a very encouraging result for further ERP research on lexical features.

CONCLUSION

Using event-related potentials, we have demonstrated that the lexical distinction between count and mass nouns is reflected by a frontal ERP effect: i.e. a more negative potential for count than mass nouns. This ERP effect was independent of any violations and proved to be functionally and topographically independent from the N400 component, challenging a primarily semantic explanation for the mass/count effect. Rather, the component resembled frontal negativities observed for grammatical function words and for syntactic violations. Thus the data suggest that ERPs can differentiate between conceptual and grammatical features in the mental lexicon, even without employing the commonly used violation paradigm.

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