Early Occipital Sensitivity to Syntactic Category Is Based on Form Typicality
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Language processing is one of the most complex cognitive tasks humans routinely engage in. Yet linguistic computation is astonishingly rapid: During spoken or written comprehension, each word is fully analyzed and interpreted in its context within 600 ms (e.g., Friederici, 2002; Marslen-Wilson, 1975; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). One of the fastest processes in this stream of computations appears to be access to a word’s syntactic category (i.e., whether it is a noun, verb, adjective, etc.). For example, a word category violation (e.g., the ungrammatical preposition “about” in the sentence fragment “I heard Max’s about story”) takes only 130 ms to affect event-related brain potentials (ERPs; Friederici, 2002; Neville, Nicol, Barss, Forster, & Garrett, 1991). This rapidity is highly surprising given that 100 to 130 ms is essentially the time window of low-level visual or auditory analysis (Di Russo, Martinez, Sereno, Pitillas, & Hillyard, 2001; Hickok & Poeppel, 2007; Tarkianen, Helenius, Hansen, Corneliussen, & Salmelin, 1999).

To explain this temporal concurrence, we recently proposed a sensory hypothesis for early effects of syntactic category violations. According to this account, predictions about sentence structure can affect modality-specific brain responses in sensory cortices. The key idea is that in reading, for example, early effects of category violations are dependent on strong visual cues to category (e.g., affixes such as the “–ed” in “reported”). When such category-marking elements are unexpected, an occipital mismatch response is elicited during word-form analysis. Using magnetoencephalography (MEG), we demonstrated that activity generated in visual cortex at 100 to 130 ms (the visual M100 response) increases when an encountered word mismatches the expected syntactic category (Dikker, Rabagliati, & Pylkkänen, 2009). This effect was particularly striking because the M100 response, which has previously shown sensitivity only to variation in stimulus noise and size, and not to linguistic variables (Solomyak & Marantz, 2009; Tarkianen et al., 1999).

In our sensory hypothesis, prediction of upcoming syntactic structure plays a crucial role in explaining the earliness of syntactic-category effects. In placing an emphasis on such predictions, our work builds on much previous research showing that in language processing, representations at multiple levels, from phonology to syntax, are predicted and preactivated. For...
example, a number of psycholinguistic studies have demonstrated that linguistic anticipation may affect eye movements (e.g., Altman & Kamide, 1999; Staub & Clifton, 2006), and expectation-based probabilistic models of language comprehension have proven successful in explaining a range of behavioral data (e.g., Hale, 2006; Levy, 2008). Recently, electroencephalography and MEG research has begun to elucidate the neural bases of these prediction effects (e.g., DeLong, Urbach, & Kutas, 2005; Lau, Stroud, Plesch, & Phillips, 2006).

Although the notion of structural anticipation helps explain the rapidity of category-violation effects in electromagnetic data, a complete theory of this phenomenon needs to characterize the nature of the category cues that the occipital cortex responds to. In the current work, we contrasted two hypotheses about the nature of these cues. Obvious candidates for the relevant category cues are affixes and other closed-class morphemes (e.g., –ness, –ly, of, about), which are highly frequent and generally visually salient, as well as strongly indicative of a specific syntactic category. Psycholinguistic research has also shown that closed-class morphemes have a special status in language processing (e.g., Bradley, 1983). Consistent with the hypothesis that the M100 category effect is dependent on the presence of closed-class morphemes, our previous study (Dikker et al., 2009) revealed an M100 effect only when the category of the unexpected item was saliently marked by a closed-class morpheme.

Alternatively, however, the relevant category cues could be sets of probabilistic form features that are indicative of a particular syntactic category. In that case, an M100 effect of unexpectedness would be obtained even for words that lack a closed-class morpheme, as long as their form is characteristic of their syntactic category. Our previous M100 findings on closed-class morphemes could easily be explained by this hypothesis because a word with a category-marking morpheme is very likely to look typical of its category.

This form-typicality hypothesis derives from research demonstrating that the words of a given syntactic category share systematic, probabilistic, form-based regularities, and that these regularities have consequences for on-line syntactic processing (Farmer, Christiansen, & Monaghan, 2006; Kelly, 1992; Monaghan, Christiansen, & Chater, 2007). In one recent study, Farmer et al. (2006) demonstrated via a corpus analysis that English nouns and verbs form clusters in phonological space that reflect the relative occurrence of certain features. Whereas most nouns and verbs are typicality neutral, containing form features that are equally common in the two categories, there are also clearly typical nouns and verbs (nouns that are more typical share fewer features with verbs and vice versa). Farmer et al. found that English speakers were faster to read typical words than atypical words. Staub, Grant, Clifton, and Rayner (2009) failed to replicate these effects; however, expectations for either a noun or a verb were potentially weakened in this study because they used a mixed design rather than the blocked (noun and verb items in separate experiments) design utilized in the original experiments by Farmer et al.

Tanenhaus and Hare (2007) argued that the findings of Farmer et al. (2006) might help explain eye movement patterns during reading: The length of first fixations could be contingent upon form-feature predictions. This would be consistent with an early visual M100 effect for words containing unexpected form features. From this perspective, the visual M100 component would be sensitive to the probabilistic distribution of form features across the entire mental lexicon, rather than being specifically tuned to detecting a small set of closed-class morphemes.

Previous electrophysiological research on lexico-semantic anticipation has already demonstrated that form predictions are not restricted to closed-class morphology. For example, Laszlo and Federmeier (in press) showed that overall orthographic similarity to a predicted word affects the amplitude of the N400 component, an ERP response sensitive to lexico-semantic expectancy (e.g., Kutas, Van Petten, & Kluender, 2006). Similar experiments in the auditory domain have shown that words that violate phonological, but not semantic, predictions generate an ERP effect that can be dissociated from the N400 response (the phonological-mismatch negativity; e.g., see Connolly & Phillips, 1994). However, both the N400 and the phonological-mismatch negativity clearly reflect later stages of processing than the MEG M100 response. Further, these studies investigated predictions for individual words, rather than expectations for syntactic categories.

To test whether, in the context of syntactic prediction, closed-class morphemes have a special status as category indicators, or whether form typicality can also serve as a category cue for the visual cortex, we examined the visual M100 effect for three types of nouns presented in expected or unexpected contexts in word-by-word reading: (a) bimorphic nouns (i.e., words with a closed-class category-marking morpheme, such as “farmer,” “princess,” and “artist”), (b) monomorphic, typical nouns containing form properties that are indicative of the noun category (e.g., “movie,” “soda”), and (c) neutral nouns (i.e., those with no clear form bias toward either nouns or verbs). The bimorphic nouns and the typical nouns we used were about equally indicative of the noun category. To manipulate syntactic context, we created sentences in which the critical noun was preceded either by an adjective (e.g., “the beautiful ____”), such that a noun would be highly expected, or by an adverb (e.g., “the beautifully ____”), which would render nouns unexpected and instead induce a strong expectation for a participle (e.g., “dressed”).

If word-category violations are detected during early visual processing exclusively on the basis of closed-class morphemes in the input, then only the bimorphic nouns would be expected to show an M100 effect of unexpectedness. Alternatively, if form typicality is sufficient, then an M100 effect would be expected for typical nouns as well. Neutral nouns would not be expected to elicit an M100 expectedness effect according to either hypothesis.
In addition to comparing the average M100 response to each noun type in each sentence context, we analyzed dipole waveforms for single-trial data. This allowed us to conduct a multiple regression analysis addressing whether the presence of a closed-class morpheme leads to an M100 effect independently of a word’s form typicality.

**Method**

**Participants**

Fifteen healthy, right-handed subjects participated (6 female and 9 male; average age = 23 years). All had normal or corrected-to-normal vision and gave informed consent.

**Materials**

Forty bimorphemic, 40 typical monomorphemic, and 40 neutral monomorphemic nouns were presented to participants in both expected and unexpected contexts (e.g., “the beautiful princess was painted” vs. “the beautifully princess was painted”). Nouns were drawn from the analysis of the CELEX corpus (Baayen, Piepenbrock, & Gulikers, 1995) conducted by Farmer et al. (2006). Farmer et al. calculated the phonological distance between each possible two-word comparison based on the number of overlapping and nonoverlapping phonetic features. They obtained a typicality score for each word by subtracting its mean distance to all verbs from its mean distance to all nouns. Typicality scores for the nouns and verbs that Farmer et al. analyzed ranged from −.632 to .498, with more highly negative scores denoting a more nounlike form, scores around 0 denoting neutrality, and more highly positive numbers denoting forms more typical of verbs. For the words in this study, the typical nouns had a mean score of −.42 (SD = .08), whereas the neutral nouns had forms that were approximately equally similar to nouns and verbs (M = .00, SD = .02). The bimorphemic nouns were also typical of the noun category (M = −.34, SD = .15), but less so than the typical nouns. Target words were matched for frequency and are listed in Appendix A in the Supplemental Material. Selecting words with suitable typicality values for our three noun types unfortunately resulted in length differences between conditions (neutral nouns were shortest, and bimorphemic nouns were longest). However, this did not appear to affect our results (see the multiple regression analysis in the Results section).

To avoid habituation, we used 240 filler sentences in which adjectives and adverbs were followed by participles (e.g., “the beautiful dressed . . .” or “the beautifully dressed . . .”). All sentences are listed in Appendix B in the Supplemental Material.

**Procedure**

While seated in a dimly lit, magnetically sealed chamber, participants read the stimuli on a screen approximately 17 in. from their head. Sentences were presented word by word, with each word appearing for 300 ms, followed by a 300-ms blank screen. Participants judged each sentence’s grammaticality after the final word was presented. The entire MEG recording session lasted approximately 40 min. Data were collected using a whole-head 275-channel gradiometer (CTF, Vancouver, British Columbia, Canada) system sampling at 600 Hz in a band between 0.1 and 200 Hz. Further details regarding the procedure and materials can be found in the Supplemental Material available online.

**Data analysis**

Data were high- and low-pass-filtered (at 1 and 40 Hz, respectively) and automatically cleaned of artifacts (approximately 10% of trials were rejected). To estimate the generating source of the M100, we used a multiple-source model (BESA Software; Brain Electrical Source Analysis 5.1, Gräfelfing, Germany) taking data from all sensors. Dipole locations did not differ across conditions, nor did the number of additional dipoles used in the model.

To test for M100 effects in the averaged data, we performed a 2 (context: expected vs. unexpected) × 3 (noun type: bimorphemic vs. typical vs. neutral) within-subjects analysis of variance (ANOVA) on the mean amplitude of a 15-ms interval centered around the average M100 peak for each condition and subject (as in Dikker et al., 2009). We used post hoc t tests to examine effects within each noun type.

To test for independent contributions of closed-class morphology and typicality to the M100 effect, we used an individual-trial mixed-effects regression analysis. We estimated peak M100 amplitude for each trial, using the previously generated source model, and then regressed amplitude against predictors for the effects of morphology, typicality, and other psycholinguistically relevant variables (listed in Table 1 and described in more detail in the Supplemental Material). To characterize how a word’s form typicality mismatches with the predicted form typicality, we estimated how far (in normalized units of typicality) the typicality of each encountered word lay from the mean typicality score of the expected word category. The coefficient for this regression term (predicted typicality mismatch) would be reliably greater than 0 if the difference between expected and encountered typicality affected the M100. To test whether closed-class morphology had a reliable independent effect, we included a Morpheme Presence (closed-class morpheme present vs. absent) × Context (expected vs. unexpected) interaction term.

**Results**

**Results for averaged data: expectedness and M100 amplitude**

Figure 1 shows the average M100 dipole activity in each condition. A 2 (context: noun expected vs. unexpected) × 3 (noun type: bimorphemic vs. typical vs. neutral) within-subjects
ANOVA on M100 amplitude revealed a main effect of context, $F(1, 14) = 4.708$, $p = .048$, $\eta^2 = .252$, and an interaction between context and noun type, $F(2, 28) = 3.614$, $p = .017$, $\eta^2 = .467$, indicating that this effect was not present in every condition. There was no main effect of noun type, $F(1, 14) = 1.113$, $p = .299$, $\eta^2 = .169$.

Pair-wise comparisons confirmed that the difference in M100 amplitude between expected and unexpected nouns was reliable for the bimorphemic nouns, $t(14) = 4.18$, $p < .001$, $\eta^2 = .56$, but also for typical nouns, $t(14) = 2.15$, $p = .049$, $\eta^2 = .25$. Neutral nouns showed no effect, $t(14) = 0.32$, $p = .75$, $\eta^2 = .01$.

Because the latency of the M100 peak varied across subjects, we repeated the analysis using each individual’s by-condition peak amplitude as our dependent measure. This analysis produced essentially identical results, with reliable differences between expected and unexpected bimorphemic nouns, $t(14) = 3.634$, $p = .003$, $\eta^2 = .49$, and typical nouns, $t(14) = 3.171$, $p = .007$, $\eta^2 = .42$, but not neutral nouns, $t(14) = 0.733$, $p = .47$, $\eta^2 = .04$.

**Single-trial analysis**

The results of the regression are presented in Table 1. Despite the model’s high deviance score, indicating a low overall fit because of the noisy individual-trial data, the results are clearly interpretable. Controlling for all other variables, predicted typicality mismatch had a reliable effect on M100 amplitude, $\beta = 3.77$, $SE = 1.52$, $t = 2.49$, $p = .016$ ($p$ value simulated using Markov-chain Monte Carlo methods): The further a word’s form typicality was from the expected word category, the greater the M100 amplitude, a finding consistent with the results in the by-condition analysis.

However, the regression failed to provide any evidence that closed-class morphemes play a special role in generating an M100 effect. The increased M100 amplitude for unexpected nouns containing a closed-class morpheme was no greater than would be expected given their predicted typicality mismatch alone, as indicated by the small and nonsignificant interaction between the variables coding for context and morpheme presence (see Table 1).

One other reliable effect emerged from the regression: Nouns encountered in an unexpected context produced a reliably larger M100 than nouns encountered in an expected context, $\beta = 2.84$, $SE = 1.36$, $t = 2.09$, $p = .04$ ($p$ value simulated using Markov-chain Monte Carlo methods). There was no effect of orthographic length, which suggests that the small length differences between conditions did not affect any of our results.

**Discussion**

The research presented in this report was designed to elucidate the remarkably rapid onset of syntactic-category effects in language processing. When analyzed using both a factorial design and a multiple regression on individual trials, the MEG visual M100 response was sensitive to form typicality, and not just to a small set of closed-class morphemes. This strongly suggests that the brain uses prior syntactic context to predict not only a word’s syntactic category (e.g., Hale, 2006; Lau et al., 2006; Levy, 2008), but also form features that are probabilistically associated with the predicted category.

A central aspect of any explanation of these occipital word-category effects is whether the effects arise in an entirely top-down fashion, or, alternatively, whether the regions generating the visual M100 house some type of category representations. Our results cannot strictly settle this issue, as it is impossible to discern whether the M100 effect we observed results from low-level form-feature matching or from a true word-category mismatch.

However, in the context of extant understanding of the visual M100 as a low-level response, it would be very surprising if the M100 generator were implicated in the processing of word category. For example, although some evidence from electroencephalography suggests that orthographic regularity affects early visual processing (Hauk et al., 2006), Tarkiainen et al. (1999) did not report any differential M100
explained in terms of a mismatch occurring at the form-feature level, and that the M100 generator is in fact insensitive to higher-level linguistic properties such as word category.

Currently, the exact nature of the form representations available to the M100 generator remains to be fully specified. For example, localization of the M100 response (Itier, Herdman, George, Cheyne, & Taylor, 2006) implicates posterior occipital areas that have been shown to be indifferent to the distinction between letters and nonletters, suggesting that there is a level of processing at the sub-letter level, but also points to slightly more anterior visual regions that have been implicated in letter-level processing (see Dehaene, Jobert, Dubus, Sigman, & Cohen, 2007, for a discussion of the functional organization of different levels of written-word processing across occipito-temporal cortex).

Our results relate to the more general hypothesis that, within a number of cognitive domains, contextual predictions might affect processing in sensory cortices (Bar, 2007). However, evidence pertaining to this hypothesis has been limited. For example, Summerfield et al. (2006) found evidence for contextual prediction in object identification, but context was defined very globally (in terms of task demands that varied between experimental blocks). In natural language processing, by contrast, context is dynamic and local. Word-category predictions are updated continuously and are not subject to conscious selective attention. Thus, our study may provide one of the first demonstrations of the role of visual cortex in contextual prediction under relatively naturalistic conditions.

**Conclusion**

This research provides new evidence for the mechanisms by which prediction allows rapid language processing, showing that probabilistic form estimates based on word-category predictions affect the earliest stages of visual analysis. Future work will need to address exactly how the occipital expectancy effects modulate subsequent processing, but the present findings offer one important step toward elucidating the cognitive and neural mechanisms underlying the ease and rapidity of language processing.

**Declaration of Conflicting Interests**

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

**Supplemental Material**

Additional supporting information may be found at http://pss.sagepub.com/content/by/supplemental-data

**References**


