Early occipital sensitivity to syntactic category is based on form typicality

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ABSTRACT

Syntactic factors can rapidly affect behavioral and neural responses during language processing, however, the mechanisms that allow this rapid extraction of syntactically relevant information remain poorly understood. We address this issue using magnetoencephalography, and find that an unexpected word category (like *The recently princess…*) elicits enhanced activity in visual cortex as early as 120ms, as a function of the compatibility of a word's form with the form properties associated with a predicted word category. Since no sensitivity to linguistic factors has been previously reported for words in isolation at this stage of visual analysis, we propose that predictions about upcoming syntactic categories are translated into form-based estimates, which are made available to sensory cortices. This finding may be a key component to elucidating the mechanisms that allow the extreme rapidity and efficiency of language comprehension.

Introduction

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 600ms (see 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 and so forth. For example, a word category violation such as the ungrammatical preposition *about* in the sentence fragment *I heard Max's about story* takes only 130ms to affect event-related brain potentials (ERPs; Friederici, Pfeifer, & Hahne, 1993; Neville, Nicol, Barss, Forster, & Garrett, 1991). This is highly surprising given that 100-130ms is essentially the time window of low-level visual or auditory analysis (Di Russo, Martinez, Sereno, Pitzalis, & Hillyard, 2001; Hickok & Poeppel, 2007; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999).

To explain this temporal concurrence, we recently proposed a so-called "sensory hypothesis" for early effects of syntactic category violations. On 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 dependant on strong visual cues to category, such as affixes (e.g., the *–ed* in reported), and 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 100-130ms (the visual M100 response) in fact increases when an encountered word mismatches with the expected syntactic category (Dikker, Rabagliati, & Pylkkänen, 2009). This effect was particularly striking because the M100, which has mainly been studied for words in isolation, had previously only shown sensitivity 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 doing so, our work builds on much previous research showing that in language processing, representations at multiple levels, from phonology to syntax, are predicted and pre-activated. For example, a number of psycholinguistic studies have demonstrated that linguistic anticipation may affect eye movements (e.g., Altmann & 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, EEG (electroencephalography) and MEG research has also begun to elucidate the neural bases of these prediction effects (e.g., DeLong, Urbach, & Kutas, 2005; Lau, Stroud, Plesch, & Phillips, 2006).

While 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. One obvious candidate for the relevant type of category cue are affixes and other closed-class morphemes (e.g., *-ness*, *-ly*, *of*, *about*), which are highly frequent and therefore 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 dependant on the presence of closed class morphemes, in Dikker et al (2009) we only found an M100 effect 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. The crucial prediction would then be that an M100 effect of unexpectedness should be obtained even for words that lack a closed-class morpheme, as long as their form is overall characteristic of the word's syntactic category. Our previous M100 findings on closed-class morphemes could easily be explained by this hypothesis, since 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 systematic, probabilistic, form-based regularities exist among the words of a given syntactic category, and these regularities have consequences for on-line syntactic processing (Arciuli & Monaghan, 2009; 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, reflecting the relative occurrence of certain features in either category. While most nouns and verbs are 'typicality neutral', containing form features that are equally common in both categories, there are also clearly typical nouns and verbs (more 'typical' nouns share less features with verbs and vice versa). Farmer et al. (2006) found that English speakers were faster to read typical words. Staub, Grant, Clifton, & Rayner (2009) failed to replicate these effects, but due to a large deviation from the original Farmer et al. studies, expectations for either a noun or a verb were potentially weakened. The fact that this difference in design attenuated the effect of typicality demonstrates the potential importance of prediction.

Tanenhaus and Hare (2007) argue that Farmer et al's findings might help explain eye movement patterns during reading: effects on 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. Crucially then, the visual M100 component should be sensitive to the probabilistic distribution of form features across the entire mental lexicon, in contrast to 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 & Federmeier (in press) show 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 which violate phonological, but not semantic, predictions generate an ERP effect that can be dissociated from the N400 response (the Phonological Mismatch Negativity, see e.g., 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: (i) bimorphemic nouns (with a closed-class category marking morpheme like *farm-er, princ-ess, art-ist*); (ii) monomorphemic 'typical' nouns containing form properties that are indicative of the noun category (e.g., *movie, soda*), and (iii) neutral nouns (no clear form bias toward either nouns or verbs). Bimorphemic nouns and typical nouns were about equally indicative of the noun category. To manipulate syntactic context, the critical noun was preceded by either an adjective (*the beautiful…*), where a noun is highly expected, or by an adverb (*the beautifully…*), rendering nouns unexpected and instead inducing a strong expectation for a participle (like *dressed*).

If word category violations are detected during early visual processing exclusively on the basis of closed-class morphemes in the input, then only bimorphemic nouns should show an M100 effect of expectedness. Alternatively, if form typicality is sufficient, then an M100 effect should be present for typical nouns as well. Under neither hypothesis should neutral nouns elicit an M100 expectedness effect.

In addition to comparing the averaged M100 responses to each noun type by 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.

2 Methods

Supplementary information is available on-line presenting further details regarding the methods and materials.

2.1 Participants

15 healthy right-handed subjects participated (6 female, average age: 23). All had normal or corrected-to-normal vision and gave informed consent.

2.2 Materials

40 bimorphemic, typical monomorphemic, and neutral monomorphemic nouns were presented to participants in both expected and unexpected contexts (e.g., *The beautiful <u>princess</u> was painted* vs. *The beautifully <u>princess</u> was painted*). Sentences were presented word-by-word (300ms on/off). Nouns were drawn from Farmer et al.'s (2006) analysis of the CELEX corpus. Farmer et al. (2006) calculated the phonological distance between two words based on the number of overlapping and non-overlapping phonetic features. Typicality scores for each word were then obtained by subtracting its distance to all verbs from its distance to all nouns. Typicality scores for the nouns and verbs in CELEX ranged from -.632 to +.498, with more negative scores denoting a more noun-like form, scores around 0 denoting neutrality, and more positive numbers denoting forms more typical of verbs. The typical noun condition had a mean score of -.42 (SD=.08), while the neutral nouns had forms that were approximately equally similar to both categories (<u>M</u> =.00, SD=.02). Bimorphemic nouns were also typical of the category (<u>M</u> =-.34, SD=.15), but less so than the typical nouns. Targets were matched for frequency and are listed in

Appendix A (available online). Deriving suitable typicality values for our items unfortunately resulted in length differences between all conditions (neutral nouns were shortest, bimorphemic nouns longest). However this did not appear to affect our results (see multiple regression analysis below). To avoid habituation, we used 240 matched filler sentences in which adjectives and adverbs were followed by participles (e.g., *the beautiful/beautifully dressed…*). All sentences are listed in Appendix B.

2.3 Procedure

Participants read the stimuli on a screen approximately 17 inches from their head, while sat in a dimly lit, magnetically sealed chamber, and judged each sentence's grammaticality after the final word. The entire recording session lasted approximately 40 minutes. Data were collected using a whole-head 275-channel gradiometer (CTF, Vancouver Canada) system sampling at a 600Hz in a band between 0.1 and 200Hz.

2.4 Data Analysis

Data was high/low pass filtered (at 1/40Hz) and automatically cleaned of artifacts (approximately 10% of trials rejected). To estimate the generating source of the M100 we used a multiple-source model (BESA Software; Brain Electrical Source Analysis 5.1) taking data from all sensors. Dipole locations did not differ over 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 (Expectation level: Expected vs. Unexpected) by 3 (Noun Type: Bimorphemic vs. Typical vs. Neutral) within-subjects ANOVA on the mean amplitude of a 15ms interval centered around the average M100 peak for each condition and subject, as in Dikker et al. (2009). Post-hoc t-tests were used 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 and typicality, and other psycho-linguistically relevant variables (listed in Table 1, and described and motivated in more detail in the supplementary materials). To characterize how form typicality mismatches with prediction, 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. This regression term, predicted typicality mismatch, should be reliably greater than 0 if the difference between expected and encountered typicality affects the M100. To test if closed-class morphology has a reliable independent effect, we included a morphology-presence by context interaction term.

3 Results

2.1 Results for averaged data: Expectedness and M100 amplitude

Figure 1 shows the average M100 dipole activity per condition. A 2 (Expectedness: Expected (noun expected) vs. Unexpected (participle expected)) by 3 (Noun Type: Bimorphemic vs. Typical vs. Neutral) within-subjects ANOVA on M100 amplitude revealed a main effect of Expectedness ($F(1,14)=4.708$, $p=.048$, $\eta^2=.252$), and an interaction between Expectedness and Noun Type ($F(2,28)=3.614$, $p=.017$, $\eta^2=.467$)

indicating that this effect was not present in each 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 M100 amplitude difference 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 ($t(14)=.32$, $p=.75$, $\eta^2=.01$).

Because the M100 peak's latency varied across subjects, we repeated the analysis using each individual's by-condition peak amplitude as our dependent measure. This 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 ($t(14)=.733$, $p=.47$, $\eta^2=.04$).

INSERT FIGURE 1 HERE

3.2 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: words whose form was less consistent with the predicted word category generated a reliably larger M100, consistent with the results in the by-condition analysis (ß=3.77, SE=1.52, $t=2.49$, $p_{MCMC}=.016$).

However, the regression failed to provide any evidence for a special role for closed-class morphemes 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 non-significant interaction between the variables coding for context and morpheme presence.

INSERT TABLE 1 HERE

One other reliable effect emerged from the regression: nouns encountered in an unexpected context produced a reliably larger M100 (ß=2.84, SE=1.36, t=2.09, p_{MCMC}=.04). There was no effect of orthographic length, suggesting that the small length differences between conditions did not affect any of our results.

Discussion

The research presented here sought to elucidate the remarkably rapid onset of syntactic category effects in language processing. Both in a factorial design and using 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 effect arises 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 results from low-level form feature matching, or rather from a true word category mismatch.

However, in the context of our extant understanding of the visual M100 as a low-level response, it would be very surprising if the M100 generator was implicated in the processing of word category. For example, although some evidence from EEG suggests that orthographic regularity affects early visual processing (Hauk et al., 2006), Tarkiainen et al. (1999) did not report any differential activity at the M100 response to letter strings compared to symbols. Similarly, in a recent MEG study using a lexical decision task, no effects of lexical factors were found before 150ms (Solomyak & Marantz, 2009). We therefore believe that our results are more plausibly 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 like word category.

At this point the detailed nature of the form representations available to the M100 generator remains somewhat open. For example, localization of the M100 response (Itier et al., 2006) points to posterior occipital areas that have been shown indifferent to the distinction between letters and non-letters suggesting a level of processing at the sub-letter level, but also to slightly more anterior visual regions that have been implicated in letter level processing (see Dehaene et al., 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 contextual predictions might affect processing in sensory cortices for a number of cognitive domains (Bar, 2007).

However, evidence pertaining to this has been limited. Summerfield et al., (2006) for example, find 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. As such, our findings 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.

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FIGURE 1 - Grandaveraged waveforms for the M100 dipole sources

Grandaveraged waveforms for the M100 dipole sources per comparison (blue = expected / red = unexpected). n=15. 15ms intervals centered around the average M100 peak are indicated by the red and blue dotted lines. Mean dipole locations and orientations (blue = expected / red = unexpected) as well as the dipoles from the individual participants (grey) are plotted per noun type. Results reveal effects of expectedness on M100 amplitude for the typical nouns and for the bimorphemic nouns, but not for the neutral nouns (= p <.05).*

TABLE 1 – Results of the linear regression analysis of single trial M100 amplitude

Predictors entered into the regression against peak M100 amplitude (Deviance = 29354, Number of observations = 3136), with their estimated coefficients, the standard error of that coefficient, the associated t statistic for the coefficient and a p value simulated using Markov-Chain Monte Carlo methods. These results reveal a reliable effect of predicted typicality mismatch on M100 amplitude: the further a word's typicality lies from its expected typicality, the greater the M100 amplitude. However, the presence of a morpheme did not interact with context: there was no specific effect of context for bimorphemic items that was not predicted by their predicted typicality mismatch.

FIGURE 1

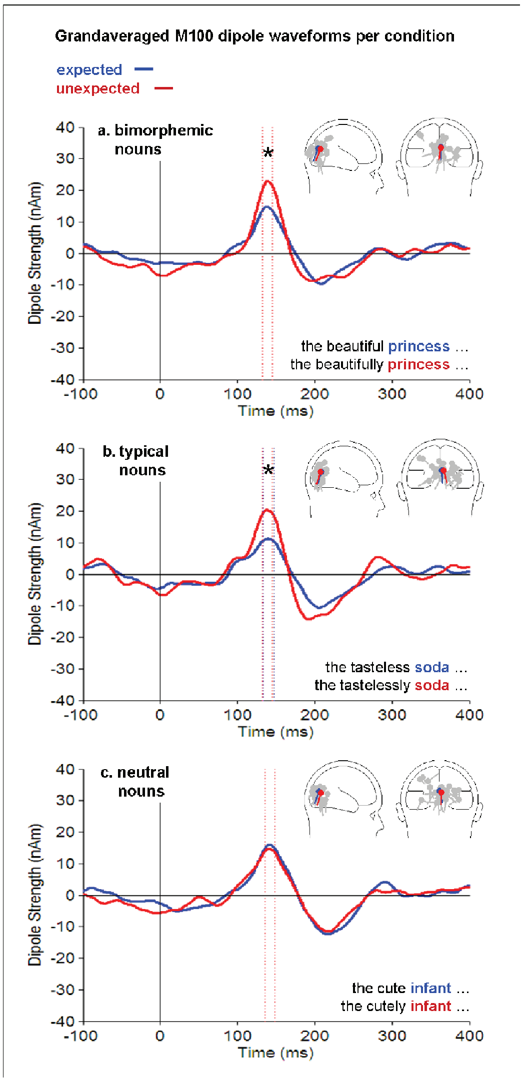
Grandaveraged M100 dipole waveforms per condition
expected
unexpected
a. bimorphemic nouns
Dipole Strength (nAm)
Time (ms)
the beautiful princess ...
the beautifully princess ...
b. typical nouns
the tasteless soda ...
the tastelessly soda ...
c. neutral nouns
the cute infant ...
the cutely infant ...

TABLE 1

	ß	Std.Error	*t* statistic	p_{MCMC}
Intercept	27.23	5.86	4.65	<0.01
Context	2.84	1.36	2.09	0.040
Morpheme Presence	-1.96	1.57	1.25	0.21
Predicted Typicality Mismatch (M = 1.61, SD = 1.07)	3.77	1.52	2.49	0.016
Orthographic Length (M = 5.66, SD = 1.46)	0.29	0.63	0.46	0.64
log Frequency (M = 5.85, SD = 1)	0.25	0.47	0.53	0.60
No. of Syllables	0.62	2.37	0.26	0.79
Orthographic Neighborhood Density (M = 3.63 SD = 4.72)	0.04	0.15	0.29	0.77
Phonological Length (M = 5.48, SD = 1.36)	0.18	0.75	0.24	0.81
Morpheme Presence * Context Interaction	0.46	1.98	0.23	0.82