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Hemispheric differences and similarities in comprehending more and less predictable sentences

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ABSTRACT

With a growing literature demonstrating the predictive nature of language processing, the current study examines contributions of the brain's two hemispheres in processing more and less probable sentence continuations. Specifically, we use the ERP method in conjunction with the visual half-field paradigm to test for hemispheric utilization of sentential constraint to (pre-)activate lexical information and resolve meaning. Taking advantage of the N400's semantic sensitivities, we find support for both hemispheres exhibiting remarkably similar involvement, across a range of message level constraint, in meaning construction. In contrast, hemispheric ERP patterns at a later processing stage differed, as reflected in an anterior post-N400 positivity (PNP) to constraint violations for words presented to the right but not left visual field (indicating a left hemisphere processing bias). We show here that hemispheric involvement in predictive sentence comprehension varies at different stages of word processing, and we examine these patterns' (in)consistencies with findings from the hemi-field and central visual presentation literature.

1. Introduction

Views of a left hemisphere (LH) specialization for language date back centuries and are well established. However, studies in more recent decades, many relying on neuroimaging techniques, have revealed that the right hemisphere (RH), too, is capable of linguistic processing, albeit with its own set of strengths (for a few examples, see Winner and Gardner, 1977; Kaplan et al., 1990; Shapiro and Danly, 1985; Gardner et al., 1983; Lindell, 2006; Federmeier et al., 2008). One outstanding question, and the focus of the current study, is how—in particular the degree and the timing with which—the brain's two hemispheres may be biased toward using sentence- and discourse-level linguistic information to facilitate processing of subsequent more or less probable language input. This investigation is conducted within a framework that assumes readers and listeners comprehend in a generally predictive manner.

The idea of language comprehenders constructing message level representations during the course of reading or listening to sentences or discourses, and then in turn using those representations to pre-activate additional linguistic information (e.g., words), is an idea that has become more widely accepted in the past decade (see DeLong et al., 2014b; Kutas et al., 2011; Kuperberg and Jaeger, 2016; Federmeier, 2007 for reviews). Online methods, such as event-related brain potentials (ERPs) and eye tracking, have been critical for establishing that there is a predictive time course to comprehension. Some of this work has relied on the N400 ERP component, a negative-going waveform peaking around 400 ms post-stimulus onset, which is part of the brain's normal response to semantic processing of a meaningful stimulus in context. N400 studies have uncovered evidence for semantic prediction at various levels, e.g., for lexical, categorically-related, event-related, and conceptually similar information (e.g., DeLong et al., 2005; Thornhill and Van Petten, 2012; Federmeier and Kutas, 1999a; Metusalem et al., 2012; Boudewyn et al., 2015). In conjunction with these findings, there is also growing support for the idea that there may be processing consequences, when predictions are not validated by the input. An important aspect of our own research (DeLong, Urbach, Groppe and Kutas, 2011; DeLong, Quante and Kutas, 2014; DeLong, Groppe, Urbach and Kutas, 2012) has been detecting effects of constraint violation: that is, if pre-activation during language comprehension runs as a sort of

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default mode, then the neural system may be caught off guard by a surprising but nevertheless sensible continuation.

In previous studies, we have reported two main findings that argue strongly for predictive sentence processing. The first is pre-critical word evidence for pre-activation of likely upcoming words. For instance, in sentence contexts such as '*The day was breezy so the boy went outside to fly*…', N400 amplitudes to English indefinite articles (*a*, *an*) preceding more and less expected critical nouns (*kite*, *airplane*, respectively) were correlated with offline cloze probability estimates of expectancy (DeLong et al., 2005). Accompanying this effect, DeLong et al. (2011), as well as DeLong et al., (2012, 2014a), reported a late (post-N400) sustained frontal, somewhat left ERP positivity to low cloze probability but plausible continuations of highly constraining sentence contexts (e.g., *airplane* in the previous example). This positivity also has been reported by others, under similar experimental circumstances, to unexpected but acceptable continuations in sentences or discourses (Federmeier et al., 2007; Thornhill and Van Petten, 2012; Moreno et al., 2002; Coulson and Van Petten, 2007; Kutas, 1993; Brothers et al., 2015; Boudewyn et al., 2015).

In fact, this late anterior ERP positivity has been proposed to be part of a larger family of late positivities that has begun to be associated with the receipt of information that disconfirms linguistic predictions. Generically, these have been referred to as post-N400 positivities or PNPs (Van Petten and Luka, 2006). Van Petten and colleagues (Van Petten and Luka, 2012; Thornhill and Van Petten, 2012) have outlined distinct PNPs, with varying scalp distributions and sensitivities: a more posteriorally distributed PNP occurring in conjunction with semantically incongruent continuations, and a more anteriorally distributed (often larger over left scalp sites) PNP arising from unexpected but sensical continuations to highly predictable contexts (also see DeLong et al., 2014a). A slightly different contrast is drawn by Kuperberg (2013), who suggests that it is event or structural prediction errors that trigger posterior PNPs (P600s) and lexical prediction errors that trigger more anterior PNPs. A common thread, however, is that anterior PNPs reflect some type of prediction violation cost.

Anterior PNPs occurring in sentence expectancy studies have only recently begun to be systematically examined. This may be due in part to the fact that unlike the widely reported N400s in such studies, the anterior PNP occurs rather inconsistently (Van Petten and Luka, 2006 provide as comprehensive a catalog as any, of such PNP findings). What is known, is that important eliciting conditions for the anterior PNP seem to be that they occur (1) to plausible continuations, or as Boudewyn et al. (2015) suggest, under circumstances in which at least some contextual support is available to trigger updating, and (2) in moderately to highly constraining sentence contexts. Thornhill and Van Petten (2012) also found that the anterior PNP can be elicited by unexpected words both related and unrelated to the expected continuation.

Various functional explanations for the anterior PNP have been proposed, but a clear picture has not yet emerged. At a more general level, it is thought to index some cost to revising discourse representations when unexpected words are received (e.g., Federmeier et al., 2007; Brothers et al., 2015). Thornhill and Van Petten (2012) and Kuperberg (2013) suggest that it indexes a sensitivity to specific lexical word forms, rather than to conceptual expectations. Other proposals range from inhibition of expected but not encountered words (Kutas, 1993), to arguments that it relates to a learning/adaptation mechanism (Kuperberg and Jaeger, 2016; Davenport and Coulson, 2013), where mental models are updated to reflect probabilities in the current environment. Kuperberg and Jaeger (2016) also suggest that PNPs may index a sort of "model switching", reflecting a reallocation of resources to a model corresponding to more immediate statistical patterns.

As mentioned earlier, observations of the anterior PNP have sometimes indicated a more left scalp distribution. While scalp distributions of ERPs are not roadmaps to underlying current sources, the somewhat lateralized scalp pattern is nonetheless suggestive of a hemispheric bias in the processing reflected by the ERPs (an idea also not incompatible with the LH's more general specialization for language). Questions about the hemispheres' roles in dealing with failed linguistic predictions are also grounded in larger debates about the roles the hemispheres play in constructing message level meaning during sentence and discourse comprehension. For instance, some have suggested that the RH, but not the LH, is "message-blind". Several studies (e.g., Chiarello, 2000; Faust, 1998; Faust and Kravetz, 1998) posit that while the LH is capable of integrating information at various linguistic levels to form message-level representations, the RH constructs meaning more on the basis of word-level association, in a bottom-up fashion. This proposition stems in part from behavioral studies manipulating sentence constraint, in which word continuations processed preferentially by the LH showed graded facilitation as indexed by lexical decision times: words processed by the RH, on the other hand, benefitted only from the highest levels of constraint. In another study (Faust et al., 1995), scrambled sentential word order led to priming effects similar to those for congruent sentences for RH-biased processing, whereas LH-biased processing benefitted only from properly ordered sentences.

In contrast to this RH "message-blind" model, others have argued that the RH *can* be involved in constructing message-level meaning. For instance, Coulson et al. (2005) combined the visual hemi-field (VHF) paradigm with ERPs to pit effects of word-level versus sentential-level priming. In the VHF technique, stimuli are presented a few degrees to the left or right of fixation in order to expose only the contralateral hemisphere to that stimulus for the first approximately 10 ms or so (Banich, 2003). The consequence of this slight head start in apprehending the stimulus results in hemispheric processing differences that carry over even into relatively late stages of processing, which, by inference, reflect how the two hemispheres handle different linguistic variables. Coulson et al. (2005) found that isolated associated word pairs and the same words pairs embedded in sentences showed similar ERP priming and context effects, respectively, regardless of visual field of presentation (VF)/hemisphere, as indexed by reduced N400 amplitudes to congruous endings. Decreases in N400 amplitude are thought to be associated with increased semantic activation levels for those items. N400 congruity effects as well as sensitivity to degree of cloze probability at various levels of message level constraint have been demonstrated for processing biased to both hemispheres by others, as well (e.g., Federmeier and Kutas, 1999b; Federmeier et al., 2005). Indeed, Federmeier and colleagues have argued that sentence level constraints facilitate semantic language processing in both hemispheres, but in somewhat different ways. For instance, Federmeier and Kutas (1999b) compared lateralized expected sentence completions to within category (related) and between category (unrelated) violations in high and low constraint sentences. Although both violation types (judged similarly implausible) showed larger N400s relative to expected items, the N400 to the related violations was reduced relative to unrelated violations only for right visual field/left hemisphere (RVF/LH) presentation and only for those contexts in which the critical nouns were highly constrained. These results were explained by the greater overlap in perceptual and semantic features of the related violation with the expected exemplar, and were interpreted as contextual information acting via semantic memory to pre-activate some of the features of the expected exemplar. In contrast, the LVF(RH) exhibited a pattern more consistent with bottom-up processing, where input is integrated only once it is received.

Also at the intersection of hemispheric sentence processing and prediction, Wlotko and Federmeier (2007) conducted a VHF version of a central presentation ERP study by Federmeier et al. (2007). Both studies used ERPs to examine the joint effects of cloze probability and sentential constraint on word processing. Plausible high and low cloze probability critical words (presented lateralized in the VHF version) continued strongly and weakly constraining sentence contexts. For central presentation, N400 amplitudes were graded by cloze probability but unaffected by whether words were embedded in strongly or weakly constraining sentences; however, an anterior PNP to low cloze probability continuations of strongly, but not weakly, constraining contexts *did* differentiate processing as a function of constraint. Federmeier and colleagues proposed that the anterior PNP perhaps reflected inhibition or revision, when processing unexpected words in highly predictive contexts. In the VHF experiment, somewhat surprisingly, there was no anterior PNP to unexpected endings of highly constraining contexts observed for presentation to either VF (although there were differences in P2s—a component linked to higher-order visual and attentional processing, Luck and Hillyard, 1994.) In particular, this had been hypothesized for RVF(LH) presentation under Federmeier's (2007) predictive LH/integrative RH account. Additionally, presentation to the two VFs yielded differing, atypical (amplitude not strictly graded by cloze probability) N400 patterns. For RVF/LH presentation, expected endings to both strongly and weakly constraining contexts showed similar reduced amplitude N400s; in contrast, for LVF/RH presentation, expected endings to strongly, but not weakly, constraining sentences showed reduced N400s. The authors proposed that the central presentation linear cloze-graded N400 and the constraint violation anterior PNP patterns may both reflect processing that only emerges via bi-hemispheric cooperation, and suggested that more fine-grained cloze probability manipulations might be required to delineate the response functions of the two hemispheres to offline sentential expectancy. Note, however, that others *have* observed anterior PNPs in VHF sentence ERP studies. For instance, Coulson and Van Petten (2007) observed larger anterior PNPs to less, relative to more, expected sentence endings, but only with presentation to the RVF/LH. Davenport and Coulson (2013) reported similar results.

To this end, Wlotko and Federmeier (2013) conducted a lateralized ERP study that presented sentence-final words that varied over a full range (0–100%) of sentence-level constraint to examine hemispheric N400s. The correlation between N400 amplitude and cloze probability for central presentation was first demonstrated by Kutas and Hillyard (1984) and later by DeLong et al. (2005). Kutas and Hillyard's original ERP study used sentence contexts with three levels of constraint (HIGH, MEDIUM, and LOW) and 2–3 levels of cloze probability (high, [medium], and low) within each constraint level. An important finding from that study was that N400 amplitude, although highly inversely correlated with an item's cloze probability ($r \approx -.9$), is insensitive to the degree to which a context's constraint is violated; in other words, the N400 does not appear to reflect a consequence for unfulfilled prediction. In Wlotko and Federmeier (2013), the researchers observed that at the extreme ends of constraint/cloze probability, highly predictable and completely unexpected items elicited similar responses across VFs/hemispheres. However, they argued that hemispheric differences manifested in weakly expected items receiving less N400 facilitation for the LVF/RH, but more N400 facilitation for RVF/LH processing. In sum, the researchers concluded that although both hemispheric N400 responses are generally graded as a function of cloze probability, neither hemispheric response looks like that of central presentation, with neural responses to weakly constrained items in particular showing differential hemispheric processing.

1.1. The current study

In the present study, we take up the dual challenges of determining potential hemispheric processing biases for graded sensitivity to message level meaning construction and constraint violation. We utilize an experimental design modeled on Kutas and Hillyard (1984) in conjunction with the VHF paradigm. Stimulus materials consist of sentences with ranges of constraint, cloze probability and, importantly—through varying *both* these factors—constraint (prediction) violation.

To test whether constraint (prediction) violations are processed similarly with presentation to the two VFs/hemispheres, we focused on potential anterior PNPs that have been observed for central presentation ERP studies. Such patterns might manifest with presentation of unexpected continuations to (A) neither, (B) both or (C) predominantly one visual field (likely the RVF/LH). Although a few studies have indicated that the anterior PNP may be more prevalent when constraint violations are presented to the RVF/LH (e.g., Coulson and Van Petten, 2007; Davenport and Coulson, 2013), this has not been a consistent finding (specifically, Wlotko and Federmeier, 2007 did not show this pattern). Thus, Outcome A would be consistent with the findings of Wlotko and Federmeier (2007), in suggesting that the anterior PNP emerges only through bicameral cooperation. Outcome B would suggest similar engagement by both hemispheres in responding to mispredicted words. Outcome C would be consistent with the LH being additionally/differentially engaged when surprising but plausible input is encountered (consistent with Coulson and Van Petten, 2007, Davenport and Coulson, 2013). Outcome C would also align with Federmeier (2007) proposal of the LH being biased toward predictive language processing, with the idea that the LH also deals differently than the RH with consequences of mis-prediction. Beyond this, such results would also implicate a particular stage of processing—separate from and later than the cognitive processes implicated by N400 modulations—that is biased toward processing by one hemisphere more than the other. While this experimental design cannot isolate the cognitive function indexed by the anterior PNP, it is nonetheless worthwhile to establish potential hemispheric biases in the processing of constraint violations, and thus hemispheric biases for linguistic prediction and its consequences.

A second goal of the study is to capitalize on the use of a stimulus set with an extended range of constraint and cloze probability to assess message level meaning construction (reflected in N400 amplitudes) when processing is biased toward individual hemispheres. In a first pass analysis, we will examine whether the LVF(RH)-presented words lead to cloze probability-modulated N400s at all. If, as some researchers have argued, the RH, like the LH, is sensitive to predictability via message level constraint, then we expect that N400 amplitude will be modulated by cloze probability with presentation to both VFs, in a graded manner; however, if the RH is less or not sensitive to message level constraint, then such a pattern should only be observed for RVF(LH) presentation. Then, following analyses in Wlotko and Federmeier (2007, 2013), in a more fine-grained analysis of N400 amplitude patterns, we probe more weakly constrained words. We will extract conditions that conceptually replicate their design, which examined the correlation of N400 amplitude and cloze probability for sentence continuations, and reported similar hemispheric patterns at high and low ends of constraint, but differing patterns for weakly constrained items. If, as Wlotko and Federmeier (2007, 2013) suggest, the LH is sensitive over a wider range of predictability than the RH, then we would expect differing hemispheric N400 amplitude patterns for the sentence continuations that are neither strongly expected nor unexpected—a finding that would be supportive of the central presentation N400 pattern only

Table 1
Sample experimental sentence stimuli.

Constraint condition	Cloze probability condition	Sample stimuli	Sentence constraint	Critical noun cloze probability
HIGH (HI)	high (hi)	*Bart did not clean his wound properly. He ended up getting an* ***infection*** *soon after.*	97%	97%
	low (lo)	*For the snowman's eyes the kids used two pieces of coal. For his nose they used a* ***berry*** *from the fridge.*	100%	< 1%
MEDIUM (MD)	high (hi)	*The pilot had to make an emergency landing in the middle of the desert. The plane was nowhere near an* ***airport*** *or a road.*	78%	78%
	medium (md)	*Joe went to the hardware store. He bought a* ***hammer*** *for half price.*	58%	58%
	low (lo)	*The cat climbed up the bird feeder. When he reached the top he saw a* ***squirrel*** *and pounced on it.*	56%	6%
LOW (LO)	high (hi)	*Valerie did not know what to make for dinner. At the supermarket she bought a* ***chicken*** *and a roast.*	19%	19%
	low (lo)	*The backpacker was hiking through the forest. She reached a clearing and spotted an* ***elk*** *and began to run.*	16%	3%

emerging as an amalgam of unique hemispheric processing contributions. However, if LVF(RH) and RVF(LH) N400 patterns are similarly graded, this would suggest that the centralized N400 pattern is not *necessarily* an emergent pattern arising from differential hemispheric contributions.

2. Materials and Methods

2.1. Materials

2.1.1. Sentence stimuli

Sentence stimuli with critical noun continuations encompassed a range of contextual constraints and cloze probabilities (see Table 1). Each trial was comprised of a context sentence followed by another sentence containing a plausible, sentence-medial, left- or right-lateralized critical noun, preceded by the appropriate indefinite article (*a, an*).[1] There were 240 different sentence pairs, each of which had two different critical continuations: a consonant-initial noun and a vowel-initial noun (both types were used as more and less expected continuations across the set of experimental materials). The resultant 480 items, which across participants were presented to the two visual fields (LVF and RVF, yielding a total of 960 lateralized stimuli), were classified into three different levels of constraint (HIGH or HI=81–100%, MEDIUM or MD=25–80%, or LOW or LO=0–24%), as a function of the cloze probability of the most frequently produced item from the sentence norming (design roughly based on Kutas and Hillyard, 1984). Within each constraint level, critical nouns ranged in cloze probability: high/low cloze probability continuations for all constraint conditions, and additionally medium cloze probability continuations for the MEDIUM constraint condition. See Table 2 for stimulus parameters.

Each participant viewed the same 240 sentence contexts, although only one of the two possible critical nouns (preceded by the appropriate *a* or *an* article) was presented, with equal numbers of *a*- and *an*-nouns presented per list. Critical nouns in the two stimulus lists (with 2 visual fields of presentation, yielding 4 lists total) were matched on factors of word frequency (Kucera and Francis written frequency count, 1967), word length, number of orthographic neighbors (Medler and Binder, 2005, MCWord database), concreteness (MRC Psycholinguistic Database: Coltheart, 1981), and overall cloze probability (see Table 3).

2.1.2. Comprehension questions

Approximately half (120) of the sentence pairs in each list were followed by yes/no comprehension questions. For two of the lists, 44% of the questions followed LVF items, 56% followed RVF items: the opposite proportions held for the other two lists. Across all four lists, an equal number of questions followed right and left lateralized stimuli.

2.1.3. Cloze probability norming

Cloze probabilities were obtained for the 480 possible experimental sentence pair contexts, each normed in an off-line sentence completion task by 31–32 UCSD student volunteers, who were compensated either with experimental credit or cash. Participants were instructed to continue each truncated context (which concluded with either the *a* or *an* indefinite article, but a single participant did not see both versions) with the word(s) they felt best completed each sentence. Cloze probability was then calculated as the proportion of individuals continuing a particular context with a particular word in the first word position of the norming response. Using these cloze probability measures, sentential constraint was determined by the most commonly provided first word in the norming responses for a particular context.

2.2. ERP participants

Thirty-two UCSD undergraduate volunteers participated in the ERP experiment for course credit or cash. Participants (23 women, 9 men) were all right-handed, native English speakers with normal or corrected-to-normal vision, ranging in age from 18 to 24 years, with a mean age of 19.8 years. Eleven participants reported a left-handed parent or sibling. Two additional participants were excluded from the analysis due to excessive eye blinks or movements.

[1] Approximately 80 of the 240 sentence pair contexts used for this experiment were taken from DeLong et al., 2005, which utilized sentences with nouns preceded by phonologically appropriate *a* or *an* indefinite articles. The remainder of the stimuli were constructed and normed for the current study.

Table 2
Constraint/cloze probability breakdowns of stimuli.

Constraint Levels			Constraint/Cloze Probability Label	Number of Items Per Condition	Cloze Probability Condition Information			Mean Constraint Violation
Label	Range	Mean			Label	Range	Mean	
HI	81–100%	92%	HI/hi	99	hi	81–100%	92%	0%
			HI/lo	41	lo	0–16%	4%	87%
MD	25–80%	47%	MD/hi	62	hi	52–80%	67%	0%
			MD/md	74	md	16–51%	33%	4%
			MD/lo	67	lo	0–15%	4%	33%
LO	0–24%	17%	LO/hi	73	hi	7–24%	14%	3%
			LO/lo	64	lo	0–6%	3%	13%

Table 3
Arithmetic means (with standard deviations) of lexical features of critical words, per list.

List	Cloze probability	Word length	Orthographic neighborhood	Concreteness rating	Word frequency
A	.37 (.36)	6.74 (2.28)	2.38 (3.89)	296 (261.82)	49.79 (89.25)
B	.36 (.36)	6.45 (2.23)	2.41 (4.21)	307 (258.08)	54.26 (133.30)

2.3. Experimental procedure

Volunteers were tested in a single experimental session conducted in a soundproof, electrically-shielded chamber. They were seated in a comfortable chair one meter in front of a computer monitor and were instructed to read sentence pairs for comprehension. Context sentences were presented in their entirety on screen, while critical word sentences were presented using rapid serial visual presentation (RSVP). Participants were told that for each RSVP sentence, one word would be presented to the left or right of central fixation. They were also informed that some sentences would be followed by comprehension questions, to which they should respond “yes” or “no” by pressing one of two hand-held buttons. Response hand was counterbalanced across participants and lists. There was a brief practice session during which eye movements were monitored by the experimenter, and feedback was given to ensure that lateralized critical words were being viewed without horizontal eye movements. Participants were asked to remain still during testing, and to avoid blinking and moving their eyes during RSVP presentation. Stimuli were presented in 10 blocks of 24 items each with short breaks in between.

Stimuli were presented in black type on a white background on a cathode-ray tube screen. Participants advanced in a self-paced manner from the context to the RSVP sentences with a button press. RSVP sentences began with a centrally presented series of crosses, on screen for a duration jittered between 1000 and 1500 ms, to orient participants to the center of the screen. RSVP words were centrally presented (except for the critical noun), for a duration of 200 ms and an interstimulus interval of 300 ms. Lateralized critical nouns were presented randomly to the left or right visual field, with the inner edge 2° visual angle from fixation. A fixation dot remained on screen throughout the trial, positioned 0.5° below the central text baseline. Participants were instructed to remain focused on this dot throughout the sentence. 2.5–3.5 s of blank screen followed the offset of the sentence final word, after which comprehension questions either did or did not appear. If there was a comprehension question, participants' button-presses served to advance to the next sentence. Following question responses, there was one second of blank screen prior to the next sentence automatically appearing on screen.

2.4. EEG recording parameters

The electroencephalogram (EEG) was recorded from 26 electrodes arranged geodesically in an Electro-cap, each referenced online to an electrode over the left mastoid. Blinks and eye movements were monitored from electrodes placed on the outer canthi and under each eye, also referenced to the left mastoid process. Electrode impedances were kept below 5 KΩ. The EEG was amplified with Grass amplifiers with a pass band of .01–100 Hz and was continuously digitized at a sampling rate of 250 samples/second.

2.5. Data analysis

Single trial epochs spanning the interval from 500 ms pre-stimulus to 1500 ms post-stimulus were extracted from the continuous EEG and screened for artifacts by computer algorithm and confirmed by visual inspection. Artifact-contaminated trials were rejected off-line before averaging. On average, 13% of LVF and 15% of RVF trials were eliminated. Data with excessive blinks were corrected using a spatial filter algorithm devised by Dale (1994). A digital band-pass filter set from .2 to 15 Hz was used on all data to reduce high frequency noise.[2] The data were re-referenced off-line to the algebraic mean of the left and right mastoids and averaged for each experimental condition, time-locked to the onset of the critical nouns.

Multiple types of statistical analyses were performed (both ANOVAs and regressions on ERP mean amplitudes), comparing both N400s and anterior PNPs for the two VFs of presentation. These different analyses allowed for examination of the influence of cloze probability and constraint (violation) as both discrete and continuous factors. All ANOVA p-values reported herein are after epsilon correction (Huynh-Feldt) for repeated measures with more than one degree of freedom. For the N400, we used a canonical time window (300–500 ms), analyzing measurements over the 15 most posterior scalp channels, where written word N400 effects are known to be the largest. For the less established anterior PNP, analyses conducted in DeLong et al., (2014a, 2011) served as guides for determining a time window and scalp region of interest (resulting in selection of 600–1100 ms as the PNP time window of analysis for the current study). The anterior PNPs reported in the earlier studies were more left lateralized; however, because we did not know if this left bias would hold for the visual hemi-field presentation, we opted to not preferentially bias our scalp region of analysis toward the left hemisphere. Instead, we extended our analysis of the PNP to the 11 most anterior scalp electrodes.

[2] The blink correction algorithm used a band-pass filter with these settings to help increase the signal to noise ratio, which improves the spatial filter. To maintain consistency across participants, these filter settings were applied to all data, regardless of whether blink correction was performed.

In addition, we also used ANOVAs to analyze visual N1 and selection negativity effects (over time windows of 100–200 ms and 300–1000 ms post noun onset, respectively, at the 10 most posterior non-midline scalp recording sites). Detecting these early ERP effects typical of visual hemifield studies offers assurance that manipulations of stimulus lateralization have been successful. And finally, as there has been some support for RVF(LH)-biased prediction based on effects of sentential constraint on the anterior P2 ERP component (e.g., Federmeier et al., 2005; Wlotko and Federmeier, 2007), we conducted an analysis between 200 and 300 ms over the same 11 anterior scalp electrodes as for the PNP analysis.

Similar to the analyses performed in DeLong et al. (2011), we also conducted repeated measures ordinary least squares regression analyses (Lorch and Myers, 1990) on the 26 scalp channels in both the N400 (300–500 ms) and PNP (600–1100 ms) time windows, separately for each VF of presentation. The response variable was mean EEG amplitude and the predictor variable (in addition to an intercept term) was either (a) critical noun cloze probability (ranging from 0% to 100%) or (b) degree of constraint violation, also ranging from 0% to 100% (calculated by subtracting the cloze probability of the presented noun from the cloze probability of most frequently provided norming response—i.e., contextual constraint). In each time window, a "t_{max}" permutation procedure (Blair and Karniski, 1993) was used to correct for the 26 multiple comparisons using a family-wise alpha level of .05. Five thousand permutations of the data were used to estimate the t_{max} distribution of all possible permutations, which is five times more permutations than the minimum recommend by Manly (1997) for this alpha level. On average, out of a possible 120 trials per VF/hemisphere of presentation, individual participants provided 103.0 trials (SD=9.4) for LVF (RH) analyses and 100.7 trials (SD=13.0) for RVF(LH) analyses.

3. Behavioral results

Participants correctly answered an average of 96% (median=96%, range=92–99%) of the comprehension questions, indicating that they were attending during the recording session. Overall, 57% of incorrect responses followed stimuli with LVF presentation, while 43% of incorrect responses followed RVF stimuli; these differences were not statistically significant [$F(1, 31)=2.27$, $p=.14$, n.s.].

4. ERP results

4.1. Early ERP effects reflecting stimulus lateralization

4.1.1. Visual N1

An early ERP potential, the visual N1 (peaking between 140–180 ms), sensitive to manipulations of visual parameters and attention (Hillyard and Anllo-Vento, 1998), is known to be larger over the cerebral hemisphere contralateral to the stimulated VF for stimuli presented peripherally. To ensure that the lateralized presentation of the critical nouns effectively stimulated the contralateral hemisphere we examined N1 amplitude (100–200 ms) at the 10 most posterior (non-midline) scalp recording sites. Collapsing across constraint and cloze probability, critical noun ERPs were subjected to an omnibus ANOVA with 2 levels of Visual Field (LVF, RVF), 2 levels of Hemisphere (LH, RH), and 5 levels of Electrode site. The factors of VF and Hemisphere interacted [$F(1, 31)=72.33$, $p<.0001$] as expected, with enhanced N1 amplitude over LH scalp sites for RVF presentation, and the opposite pattern for LVF presentation (Fig. 1).

4.1.2. Selection negativity

We also examined a contralateral selection negativity—an ERP

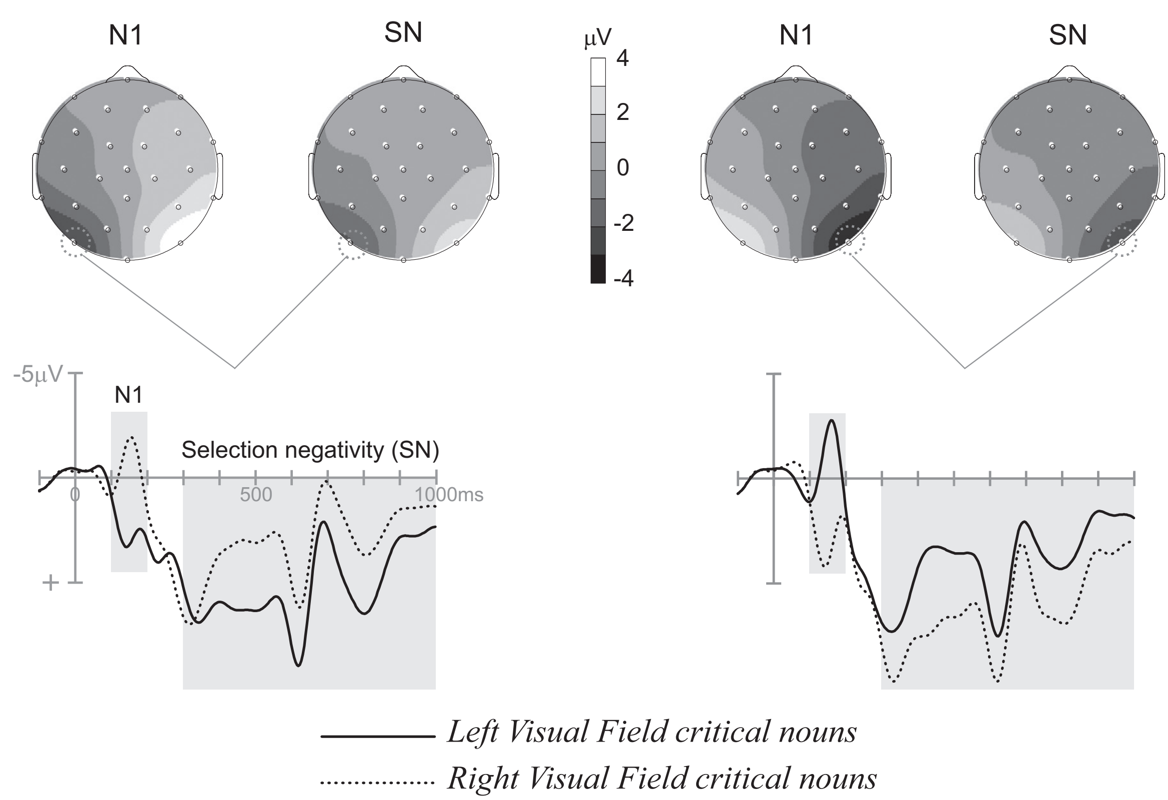

Fig. 1. Visual N1 (100–200 ms) and selection negativity (300–1000 ms) effects. Shown at a left and at a right occipital electrode, with corresponding scalp distributions calculated as the difference between the mean ERP amplitude of critical words presented to the two VFs (contralateral minus ipsilateral for each occipital site).

response that has similarly been observed in several prior studies using lateralized language stimuli (e.g., Federmeier and Kutas, 1999b, 2002; Coulson et al., 2005; Federmeier et al., 2005; Neville et al., 1982). To characterize this effect, which manifests as a sustained negativity effect over lateral posterior electrode sites, we performed the same ANOVA as for the N1, but used a 300–1000 ms time window. Like the visual N1, factors of VF and Hemisphere interacted in the expected way [$F(1, 31)=74.59$, $p<.0001$], with LVF stimuli more negative over the RH, and RVF stimuli more negative over LH sites (Fig. 1).

4.1.3. Summary of early ERP effects of visual lateralization

Taken together, the expected modulations of the visual N1 and the selection negativity by visual field assured us that our manipulation of stimulus lateralization was successful.

4.2. P200

Per Wlotko and Federmeier (2007), where a P2 effect of constraint was found, in which strongly constrained sentence endings showed larger P2s than weakly constrained endings for RVF (LH) but not LVF (RH) items, we conducted a similar analysis. Between 200–300 ms, at the 11 most anterior electrodes, mean amplitude measures were subjected to an omnibus ANOVA with 2 levels of VF (LVF vs. RVF) and 3 levels of Constraint (HIGH, MEDIUM, and LOW constraint, each collapsing across cloze probability). There were main effects of both VF [F (1, 31)=13.45, $p=.0009$] and Constraint [F (2, 62)=12.79, $p_{HF}<.0001$], with increasing P2 amplitude as sentence constraint increased and generally larger P2s for nouns presented to the RVF(LH). Notably, however, there was no significant interaction of VF with Constraint [$F(2, 62)=.28$, $p_{HF}=.7602$, n.s.]. Overall then, Constraint modulated P2 amplitude for both hemispheres similarly, with increasing amplitude to nouns continuing more constraining sentence contexts.

Although we conducted this analysis in line with those done in previous studies where P2 constraint effects were reported, one concern was that the results might be reflecting some overlap in timing and scalp distribution with the early portion of the typically widespread and temporally adjacent cloze probability-sensitive N400. Thus, instead of being an early ERP effect sensitive to some type of constraint-based tuning, the pattern might actually be reflecting more stimulus-driven processing of the presented noun. One way to address this is by limiting our constraint analysis to only the low cloze probability items for each of the three constraint levels. This way, cloze probability is held relatively constant while examining effects of constraint. To test this possibility, an ANOVA was conducted using 2 levels of VF (LVF, RVF), 3 levels of Constraint/cloze (HI/lo, MD/lo, and LO/lo constraint), and 11 anterior Electrode sites. Here, unlike the cloze probability-collapsed analysis, there were no significant main effects of either VF [$F(1,31)=2.22$, $p=.1465$, n.s.] or Constraint [F (2, 62)=.29, $p_{HF}=.7467$, n.s.].

In sum, although there was a pattern of increased P2 positivity with increasing constraint in both hemispheres when constraint levels were collapsed across cloze probabiltiy, this pattern disappeared when low cloze probability was held constant. These results point to brain activity in this time period likely reflecting the same processing that continues into the N400 time window.

4.3. Noun N400 cloze probability analyses

4.3.1. N400 discrete analyses

To examine effects of cloze probability on N400 amplitude, ERP mean amplitude was measured between 300–500 ms and subjected to an omnibus ANOVA consisting of two levels of VF (LVF, RVF), three levels of Constraint (HIGH, MEDIUM, LOW), two levels of Cloze Probability (higher and lower[3]), and 15 levels of electrode. The following main effects on ERP mean amplitude were observed: VF [$F(1, 31)=8.18$, $p=.0075$], with LVF(RH) more negative than RVF(LH) (2.95 μV, 3.66 μV respectively); Constraint [$F(2, 62)=40.42$, $p_{HF}<.0001$], with increased negativity as constraint decreased (HIGH=4.40 μV, MEDIUM=3.53 μV, and LOW=1.98 μV); and Cloze Probability [$F(1, 31)=73.69$, $p<.0001$], with low cloze more negative than high cloze (2.06 μV, 4.54 μV respectively). There were no significant 2- or 3-way interactions of VF with Constraint and/or Cloze Probability. However, there was a significant interaction of Constraint and Cloze Probability [$F(2, 62)=17.19$, $p_{HF}<.0001$]. To further examine this interaction, as well as assess planned comparisons for the conditions within each VF, pairwise comparisons were conducted. ERPs are shown in Fig. 2(a–f), and results of the statistical analyses are shown in Table 4.

For both LVF(RH) and RVF(LH), for HIGH and MEDIUM, but not LOW, constraint contexts, there were statistically significant main effects of noun cloze probability on N400 amplitude in the expected direction: the lower the cloze probability, the larger the N400 amplitude.

4.3.1.1. VF N400s and cloze probability range. For a more direct comparison with Wlotko and Federmeier's (2013) observation that for LVF/RH-biased processing, N400s to words continuing weakly constraining contexts pattern more like low cloze probability continuations, whereas the same words with RVF presentation showed ERP patterns more closely resembling those of higher cloze probability continuations, we also conducted an ANOVA on N400 (300–500 ms) mean amplitude utilizing the more continuous range of cloze probabilities afforded by our stimuli. Adding back in the MEDIUM/medium constraint/cloze probability condition, and thus disregarding the factor of Constraint (a factor which in and of itself is not known to correlate with N400 amplitudes, see Kutas and Federmeier, 2011), our test included 2 levels VF, but now 7 levels of Cloze Probability, and 15 levels of Electrode. This analysis revealed a main effect of Cloze Probability [$F(6, 186)=40.97$, $p_{\mathrm{HF}}<.0000$], with increasingly larger N400s to lower cloze probability nouns (with the exception of RVF(LH) HI/lo and MD/lo continuations). There was also a main effect of VF [$F(1, 31)=10.08$, $p=.0034$], with LVF(RH) nouns on average showing greater negativity relative to RVF(LH) nouns. There was, however, no significant interaction of VF with Cloze Probability [$F(6, 186)=1.53$, $p_{\mathrm{HF}}=.1823$, n.s.]. See Fig. 3.

To further examine the N400, we conducted additional analyses modeled on those of Wlotko and Federmeier (2013). One of the main findings from their report was that RVF/LH items were facilitated over a broader range of predictability than LVF/RH items, even though N400 hemispheric processing did not differ significantly at the extreme ends of expectancy—i.e., when they compared "Strongly Expected" words (with 90–100% cloze probability) to "Unexpected" words (those continuing sentences with up to 42% constraint, with an average cloze probability of 3%). We similarly tested the extremes of predictability in our own data by comparing difference waves formed by point by point subtractions across the epoch for each VF (see Fig. 4), in this case subtracting HI/hi items (mean cloze probability=92%) from LO/lo items (3% mean cloze probability). Like Wlotko and Federmeier (2013), our ANOVA on the magnitude of the N400 effect between 300 and 500 ms over the 15 most posterior electrode sites indicated no significant effect of VF [$F(1,31)=2.69$, $p=.1109$], see Fig. 4A. However, Wlotko and Federmeier (2013) go on to contrast their Unexpected items with "Weakly Expected" items (those with 10–50%

[3] Note, that in order to conduct this analysis, the MEDIUM constraint/medium cloze probability condition was dropped.

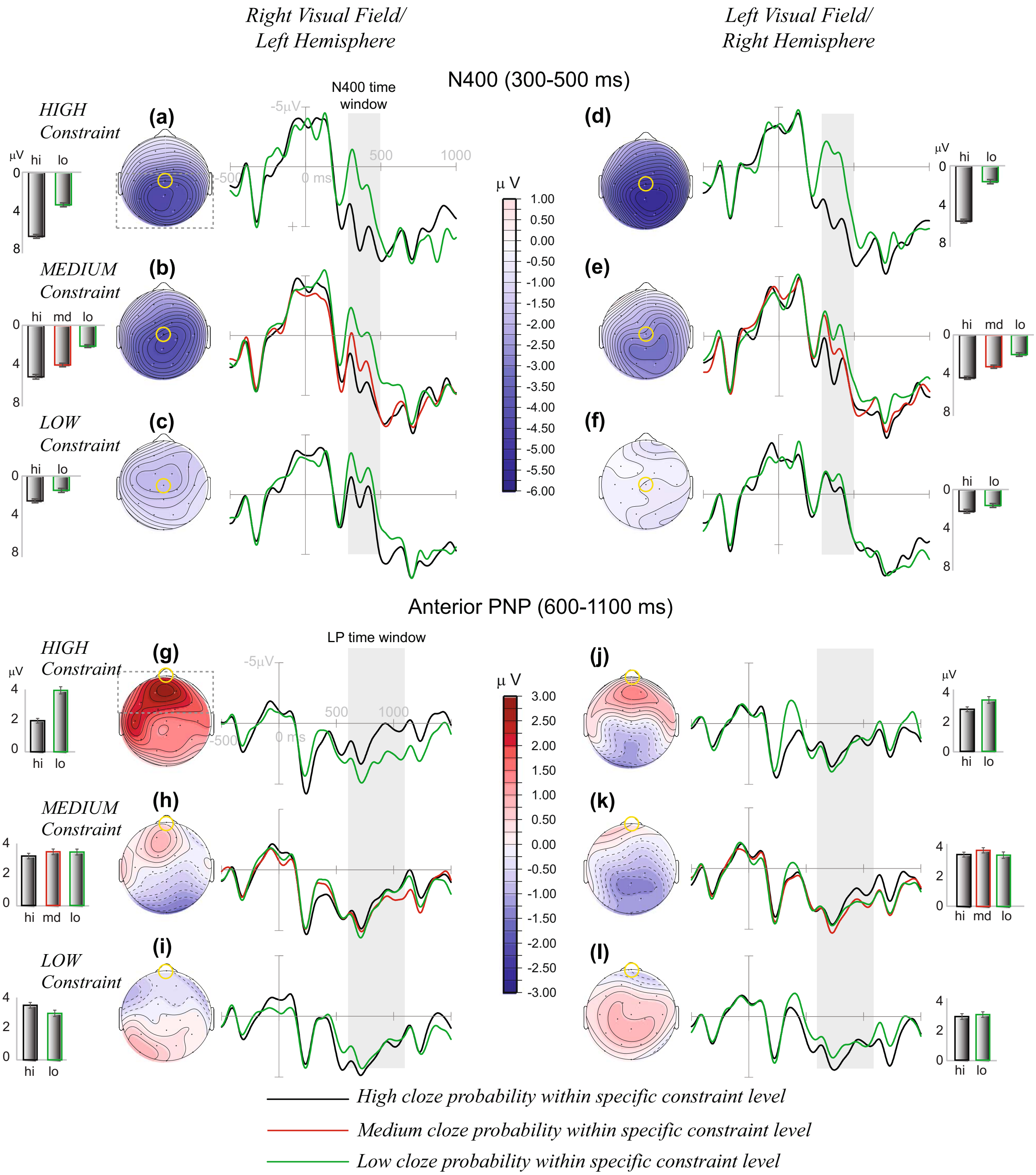

Fig. 2. Within VF and constraint level grand average ERPs. ERP traces at single representative channels (scalp locations indicated by gold circles) for N400s and anterior PNPs. Gray columns highlight time windows and dotted line gray boxes indicate scalp regions over which ANOVAs were calculated for respective effects. Topographic scalp maps of effects of low-minus-high cloze probability within each constraint level and VF during the (*a-f*) N400 (300–500 ms) and (*g-l*) anterior PNP (600–1100 ms) time windows are also shown. Bar graphs of condition ERPs averaged over respective scalp regions of interest (15 posterior channels for N400, 11 anterior channels for PNP) are also shown. Error bars indicate SEM.

cloze) and find that the effect of expectancy for Weakly Constraining contexts was larger for RVF(LH) than LVF(RH) processing —a finding also noted in Wlotko and Federmeier (2007). For a similar comparison, we derive difference waves by subtracting our MD/md condition (16–51% cloze, mean=33%) from our LO/lo condition (Fig. 4B). Here our results differ from those of Wlotko and Federmeier (2013) in continuing to find no significant difference between VFs [$F(1,31)=.91$, $p=.3464$]—a finding *inconsistent* with the idea that the RVF(LH) necessarily shows more facilitated processing of weakly constrained items than the LVF(RH). Wlotko and Federmeier (2007 and, 2013) also reported that the effect of constraint is larger for LVF(RH) than RVF(LH) processing, based on their finding of significantly larger effects for the LVF(RH) than RVF (LH) in comparisons of Expected vs. Weakly Constrained items. We attempt to replicate their analysis by contrasting our HI/hi with MD/md items in the two VFs (Fig. 4C). Our ANOVA reveals, again,

Table 4
ANOVA main effects of cloze probability within constraint levels by VF.

Constraint	Cloze probability levels	RVF (LH)		LVF (RH)	
300–500 ms (N400) over 15 posterior scalp electrodes					
HIGH	high, low	$\mathbf{F(1, 31)=23.04, p<.0001}$	Fig. 2a	$\mathbf{F(1, 31)=53.59, p<.0001}$	Fig. 2d
MEDIUM	high, low	$\mathbf{F(1, 31)=24.91, p<.0001}$	Fig. 2b	$\mathbf{F(1, 31)=38.28, p<.0001}$	Fig. 2e
LOW	high, low	$F(1, 31)=1.48, p=.2331$, n.s.	Fig. 2c	$F(1, 31)=.19, p=.6660$, n.s.	Fig. 2f
600–1100 ms (PNP) over 11 anterior scalp electrodes					
HIGH	high, low	$\mathbf{F(1, 31)=11.88, p=.0017}$	Fig. 2g	$F(1, 31)=.92, p=.3459$, n.s.	Fig. 2j
MEDIUM	high, low	$F(1, 31)=.54, p=.5864$, n.s.	Fig. 2h	$F(1, 31)=.10, p=.9084$, n.s.	Fig. 2k
LOW	high, low	$F(1, 31)=1.08, p=.3056$, n.s.	Fig. 2i	$F(1, 31)=.10, p=.7521$, n.s.	Fig. 2l

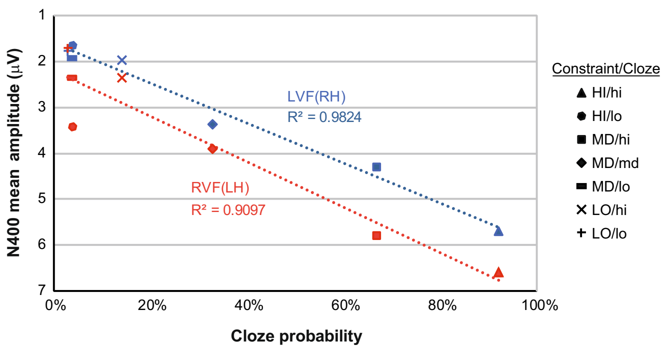

Fig. 3. N400 mean amplitude plotted by cloze probability for constraint/cloze probability conditions. Mean amplitudes are shown by VF/hemisphere. Best-fit linear trend lines using least squares method are plotted, along with R-squared values.

no significant magnitude difference in the N400 effects between the two VF/hemispheres [$F(1, 31)=.35$, $p=.5570$].

4.3.2. N400 regressions with cloze probability

In the N400 time window, there were significant positive correlations of cloze probability with mean EEG amplitude, i.e., more negative ERPs (larger N400s) with decreasing cloze probability for both the LVF(RH) and RVF(LH), at not only the 15 most posterior scalp electrodes utilized for the ANOVA analyses, but even more widespread, over all but the most left prefrontal electrode sites (Fig. 5A and B). This correlational pattern is consistent with the scalp topography of the observed discrete N400/cloze pattern in this study, as well as previous demonstrations of noun N400 mean amplitude-cloze probability correlations (DeLong et al., 2005) and canonical visual word N400s, more generally.

4.4. Noun anterior PNP constraint violation analyses

4.4.1. Anterior PNP discrete analyses

Similar to our discrete N400 analysis, we conducted an omnibus ANOVA on anterior PNP mean amplitudes between 600–1100 ms, using two levels of VF (LVF, RVF), three levels of Constraint (HIGH, MEDIUM, LOW), two levels of Cloze Probability (high and low), and 11 levels of Electrode (located over the frontal-most scalp sites). These tests indicated no significant main effects of either VF or Constraint, but there was a marginally significant main effect of Cloze Probability [$F(1, 31)=3.42$, $p=.0739$], with low cloze nouns exhibiting greater *positivity* than high cloze nouns (3.30 µV, 2.87 µV respectively). The interaction of Cloze Probability with Constraint was also marginally significant [$F(2, 62)=3.13$, $p_{HF}=.0509$]. To further examine this interaction, as well as assess planned comparisons for the conditions within each VF, we conducted pairwise comparisons within each constraint level, similar to the analyses performed for the N400. ERPs are shown in Fig. 2 (g–l), and results of the statistical analyses are indicated in Table 4. These tests indicated that the only significant main effect of constraint violation was within HIGH constraint contexts presented to the RVF(LH); for these sentences, low cloze probability noun mean

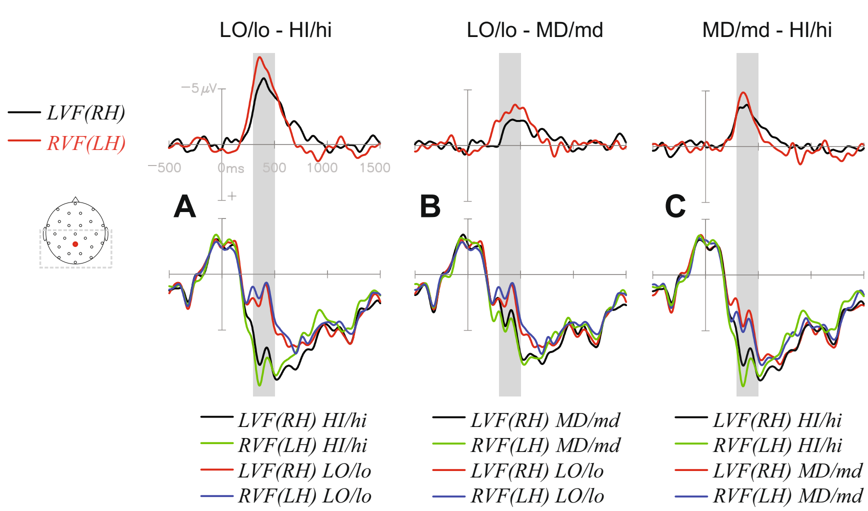

Fig. 4. N400 difference wave comparisons across VF/hemisphere. Difference waves (top row) were computed within VF/hemisphere over 15 posterior electrode sites (indicated by dotted line box on scalp map), and were derived from subtractions of individual condition ERP waveforms depicted in bottom row. None of the following VF differences in the N400 effect (analyzed from 300 to 500 ms, indicated by highlighted gray areas) reached statistical significance: for (A) the extreme ends of expectancy, (B) unexpected vs. weakly expected items, or (C) weakly expected vs. expected items.

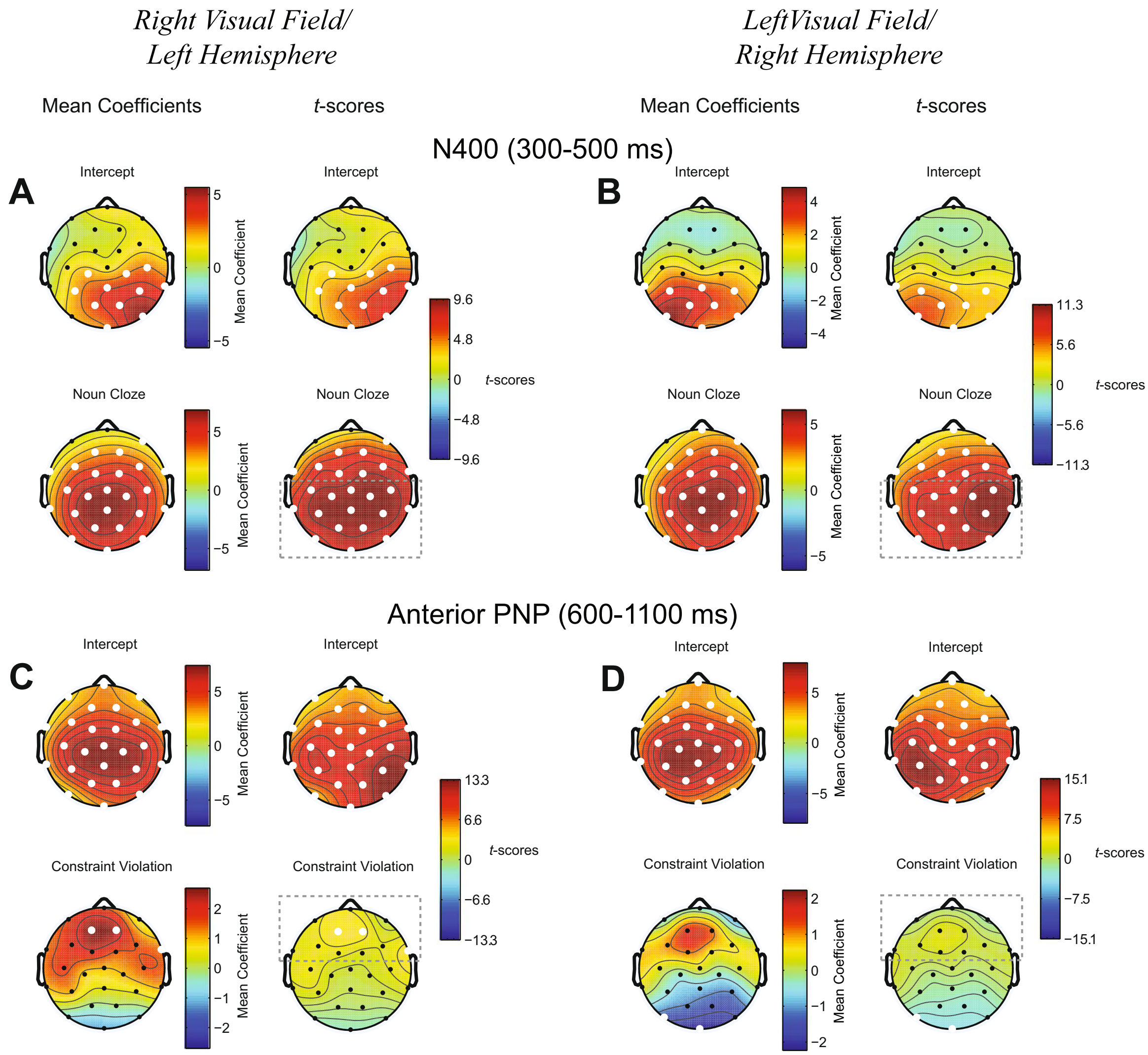

Fig. 5. Repeated measures regression analyses for both visual fields of presentation. Scalp topographies of noun ERP mean amplitude correlations with either cloze probability during the N400 time window (Figs. 5A, 5B), or with constraint violation during the anterior PNP time window (Figs. 5C, 5D). In A-D, left-most scalp maps show the mean coefficients for each predictor at each channel: right maps visualize the regression coefficients as *t*-scores (i.e., the mean coefficient divided by the standard error of the mean), to give a sense of how reliably the coefficients differ from zero across participants. For A and B, warmer-colored (red) shading indicates more negative ERP responses (larger N400s) with decreasing cloze probability. For C and D, warmer-colored (yellow) shading indicates increasing ERP positivity with increasing constraint violation. The *p*-values of significant correlations (indicated by white electrodes) range from $.000000 \le p \le .039200$ for noun cloze probability between 300 and 500 ms, and from $.011000 \le p \le .032800$ for constraint violation between 600 and 1100 ms. Regions of interest analyzed in the ANOVAs are indicated with gray dashed boxes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

amplitude exhibited a greater anterior positivity (3.59 μV) relative to that of high cloze probability nouns (2.36 μV).

4.4.2. Anterior PNP regressions with constraint violation

For the anterior PNP analysis, noun ERP mean amplitude was regressed against constraint violation (Fig. 5C and D). For LVF/RH-biased processing, there were no significant correlations observed at frontal scalp sites. In contrast, RVF/LH-biased processing showed an isolated pattern of significant *t*-scores at two medial prefrontal electrodes and at one right lateral frontal electrode. This pattern is consistent with the findings from the discrete analysis, indicating that when using more continuous measures, the anterior PNP increased in amplitude the more that contextual expectations were violated. We point out that for the LVF(RH), at two posterior occipital scalp electrodes there were significant correlations of ERP mean amplitude with constraint violation—but in the opposite direction; that is, the more that constraint violation increased, the more negative-going the ERP—an effect that we attribute to possible carryover from the N400 time window.

4.5. Summary of noun N400 and anterior PNP results

Typical patterns of increased N400 negativity with decreased cloze probability were present for HIGH and MEDIUM, but not LOW, constraint levels for both VFs of presentation. Only for very weakly constraining contexts then, was processing of more and less probable words not differentiated by N400 mean amplitude in either hemisphere. In addition, while LVF(RH) nouns overall exhibited more negative ERPs than RVF(LH) nouns, VF and cloze probability did not interact. Hemispheric N400 responses to weakly constrained words were remarkably similar in the present study. Taken together with the regression analyses, where VF correlation patterns of cloze probability with N400 mean amplitude were highly overlapping, none of our multiple analyses yielded results that point to hemispheric differentiation in processing of more and less expected sentence continuations as reflected in the N400.

However, at anterior scalp locations in a post-N400 extended time window (600–1100 ms post noun onset), our analyses revealed significant ERP differences within high constraint contexts presented to the RVF(LH), with low cloze probability continuations showing a greater anterior positivity than high cloze words. This pattern was also evident when constraint violation was examined as a more continuous measure, with a pattern of late anterior positivity for RVF(LH) but not LVF(RH) processing. Together, these results suggest differential processing between the hemispheres for an ERP pattern that has previously been linked to consequences to mis-predicting.

5. Discussion

The overarching goal of this study was to determine whether, and if so the extent to which, the two cerebral hemispheres differentially utilize written sentence context to predictively construct and resolve message-level meaning during on-line language comprehension. Our two main research questions focused on whether the LH and RH make use in a similar manner of sentential constraint to ease semantic processing (as indexed by N400 responses to critical noun continuations), and also whether there is hemispheric evidence (and/or bias) for a "misprediction consequence", and thus predictive processing, manifest in an anterior PNP.

For the question of sensitivity to message level constraints, semantic processing was facilitated by context in a highly graded manner for both VFs/hemispheres. Similar hemispheric N400 patterns argue for more nuanced usage of accrued contextual representations (as opposed to just lexically-based meaning construction or anomaly detection) for the RH than has sometimes been described. In addition, our results suggest that the two hemispheres use context in highly similar ways to activate semantic information, in all but the least constraining sentential contexts.

Regarding our second question, we set out to test whether there is (in particular, a left) hemispheric bias in the processing of sentential constraint violations. Federmeier and Kutas, (1999a) and Federmeier (2007) proposed, based on N400 findings from VHF studies, that the LH uses sentential context in a top-down manner to pre-activate upcoming linguistic content, while the RH is less predictive, relying more heavily on bottom-up processing. In parallel, findings of anterior PNPs to constraint violations in central presentation studies have been interpreted as evidence there are processing consequences when contexts constrain toward words that are not subsequently encountered. However, evidence for such PNPs in subsequent hemispheric ERP work is mixed. Although Coulson and Van Petten (2007), as well as Davenport and Coulson (2013), observed LH-biased anterior PNPs to less expected sentence continuations, Wlotko and Federmeier (2007)—specifically testing for such a response—did not, leading them to suggest that the central presentation anterior PNP response to prediction violations may emerge only through hemispheric cooperation. In the current study, our finding of a constraint violation-graded anterior PNP for RVF/LH-biased processing is thus a novel, and important, result, because it demonstrates that at least under some circumstances, the hemispheres exhibit differential prediction-related processing. These results imply that contextual representations are formed and information pre-activated by the time critical sentence input is encountered, and argue for a mechanism that relies at least in part on constraint-based expectancies instead of solely on bottom up information for comprehension. We discuss some implications of both of these findings, as well as those from our P2 analysis, below.

5.1. Frontal P2

With findings from previous research as our guide, we explored P2 amplitudes as a function of contextual constraint and hemisphere. Previous lateralized studies (Federmeier et al., 2005; Wlotko and Federmeier, 2007) noted increases in P2 amplitude correlated with increased contextual constraint for RVF/LH but not LVF/RH processing. Conducting similar analyses, in the current study we observed no such hemispheric differences; rather, both hemispheres showed increased amplitude P2s with greater constraint when constraint conditions were collapsed across varying cloze probability levels. However, when cloze probability was controlled by comparing only the low cloze probability continuations for HIGH, MEDIUM and LOW constraint contexts, there were no overall or hemispheric effects of constraint. We are thus inclined to believe that the observed P2 amplitude differences were more consistent with early stage N400 cloze probability-related processing, which would yield a similar ERP pattern.

5.2. Hemispheric sensitivity to message level constraint: N400

Both discrete and continuous analyses revealed that regardless of VF of presentation, cloze probability modulated N400 amplitude in a manner similar to that for central presentation; that is, as noun cloze probability increased, N400 amplitude decreased (i.e., ERP mean amplitude became more positive), in an approximately linear manner. These findings are consistent with lateralized ERP studies that have found decreases in N400 amplitude for expected relative to unexpected endings in highly constraining contexts for initial presentation to either hemisphere (e.g., Federmeier and Kutas, 1999b; Coulson et al., 2005; Wlotko and Federmeier, 2007, 2013). Thus, *both* hemispheres can use accruing context incrementally, with relatively similar ease or difficulty in processing more or less expected sentence continuations.

These N400 patterns argue against proposals that semantic activation is invariably and across-the-board broader and weaker for the RH, but more focal for the LH (e.g., Beeman et al., 1994). Both hemispheres benefited from fine-grained constraint provided through facilitative contexts with similar time-courses and over a similarly broad posterior scalp region. With our sentential stimuli, we argue that the N400 contextual facilitation effects for both hemispheres emanate from message-level, rather than lexical-level, constraint. This point is relevant because it challenges proposals that RH priming effects are mainly due to lexical level priming (e.g., Chiarello et al., 2001; Faust, 1998). Based on our stimulus constructions, we doubt that lexical-based priming could sufficiently explain these hemispheric effects.

A more subtle point, however, is that our N400 VF findings were not consistent with those of Wlotko and Federmeier (2007, 2013), who reported that both hemispheres deviate, in different ways, from the strongly linear (fully graded) pattern of central visual presentation N400 data. Wlotko and Federmeier (2013) argued that although N400 patterns to items at the extreme ends of cloze probability are alike across VFs, the LH facilitates moderately to strongly predictable completions more than would be expected on the linear model, and the RH facilitates weakly to moderately constrained information less than would be predicted on a linear model. In the current study, we did not observe these patterns. Across discrete and continuous analyses, and over statistical tests which contrasted N400 patterns to weakly expected items with both un- and highly expected items, no interactions with VF were found. Overall then, as evidenced in Fig. 3, N400 patterns for both VFs in our study showed remarkably similar highly linear patterns,[4] on par with those observed for central presentation

[4] The exception to the pattern of increasing N400 amplitude with decreasing cloze probability across the 7 conditions and 2 VFs, is for the HIGH/low, and possibly MEDIUM/low, RVF(LH) nouns. We believe that this more positive "bump" in N400 amplitude likely is a consequence of an overlap in timing with the onset of the anterior PNP. It is possible such overlap might lead to the slight deviation from

nouns in other studies (e.g., DeLong et al., 2005). We hesitate to stake too much on the lack of a discrete N400 effect for the LOW constraint contexts in our study, given that the high and low cloze probability nouns at this end of constraint vary, on average, by only 11%, and although not significantly different, the N400 mean amplitudes for the high and low cloze nouns vary in the typical direction (low cloze more negative than high cloze).

While in general we agree that the central presentation N400 reflects contributions of both cerebral hemispheres, our study does not offer evidence to support the idea that the hemispheric N400 contributions are always unique, and that the central presentation N400 is necessarily an emergent pattern (per Wlotko and Federmeier, 2013). Across sentence studies, the hemispheric N400 response seems to vary most to weakly constraining contexts. It is worth noting that for sentences like these, that are not at such extreme ends of constraint (neither completely nor not-at-all constraining), there are different ways in which they may be weakly constraining: e.g., there may be several close competitors or alternately, a wide variety of possible continuations. Perhaps, then, stimulus differences like these may play a role, and at a minimum could be accounted for or reported in future experimental designs.

5.3. *Hemispheric processing of constraint (prediction) violations: anterior PNP*

Our finding of an anterior PNP (here, with RVF/LH processing) to low cloze probability continuations of highly constraining sentences adds to a growing list of studies—primarily using central visual presentation—reporting this ERP response. Our result is compatible with observations that the pattern occurs as a consequence of a lexical prediction error (Thornhill and Van Petten, 2012), to plausible but unexpected continuations to constraining sentences (DeLong et al., 2014a), and under circumstances in which some contextual support is available to trigger contextual updating (Boudewyn et al., 2015). Although our results cannot distinguish between various claims about its functional significance, on the surface, our lateralized anterior PNP is potentially compatible with any of the following proposals: (a) a cost for revising an already pre-activated contextual representation in working memory (Brothers et al., 2015; Kuperberg, 2013); inhibitory processes required to suppress highly pre-activated but not received words (Kutas, 1993); conflict monitoring and/or resolution (Kolk and Chwilla, 2007); or an adaptive learning process that accounts for the current environment's statistical structure (e.g., Kuperberg and Jaeger, 2016). The new piece that our study adds to the puzzle is that whatever the component's functional correlate, it reflects processing preferentially handled by the brain's left hemisphere.

In the later time window, only RVF/LH presented words exhibited an increased amplitude anterior PNP with increased constraint violation. This finding is consistent with reports of similar ERP patterns observed primarily for central presentation prediction violations. It also is in line with the LH bias for similar anterior late positivities observed by others (e.g., Kutas, 1993; Federmeier et al., 2007; Kutas, 1993; Coulson and Van Petten, 2007; Davenport and Coulson, 2013; Coulson and Wu, 2005; Brothers et al., 2015). It suggests a dichotomy between the predictive processing mechanisms of the two cerebral hemispheres, with the LH engaging in different or additional processing when constraint-based prediction fails. Our findings show that there is a probability-sensitive consequence to pre-activating but not receiving upcoming linguistic input, which is biased towards LH processing. Much like the graded prediction findings reported in DeLong et al. (2005), our anterior PNP correlations here are consistent with graded constraint violation processing. While the anterior PNP is most evident for sentence contexts in which there is a strong expectation for a particular word, the regressions indicate that the response may also extend to less constraining contexts, for which there may not be a single, highly expected continuation.

There are a number of possible interpretations of the hemispheric asymmetry of the anterior PNP in our study. One relatively straightforward explanation is that under constraining conditions, the RH adopts a more-wait-and-see strategy when processing linguistic inputs. Federmeier et al. (2008) discuss this possibility extensively, suggesting that a system in which one hemisphere processes more predictively and the other relies more on bottom-up processing, would be well suited for handling the tradeoff between speed and flexibility that natural language comprehension demands. Another possibility, in line with the RH coarse coding hypothesis (e.g., Beeman, 1998), is that the RH may also pre-activate, but with a wider range of alternatives and at weaker levels than the LH. Thus, there would not be as much of a "misprediction consequence" when an unexpected continuation is received, because the RH may be less committed to a single or narrow set of possible continuations. Yet another explanation is that both hemispheres pre-activate projected upcoming linguistic information in a similar manner and to a similar degree; however, if the anterior PNP, for instance, turns out to reflect inhibition of strongly contextually pre-activated continuations, less inhibition in the RH than in the LH would be consistent with what has been proposed about a "slower-acting" RH that maintains semantic information in working memory for more extended periods of time (Burgess and Lund, 1998). Again, this fits with the notion of a multi-approach (hemispheric) parser hedging its predictive bets by having a sort of fail-safe system in place for instances when alternatives to predicted continuations must be pursued. While both hemispheres appear capable of exhibiting fine-grained sensitivity to contextual information, it seems likely that these sensitivities could ultimately be weighted by different factors, be used for different cognitive goals, and/or could have their consequences over variable temporal durations.

Regarding possible reasons for the discrepancy in hemispheric anterior PNP findings between the current study and Wlotko and Federmeier (2007), we can only speculate. The purpose of such speculation goes beyond simply identifying differences in results from two somewhat similar experimental designs. Namely, these explorations begin to home in on possible eliciting conditions and factors influencing when anterior PNPs occur and when they do not, which in turn could help to shed light on the ERP's functional significance. This seems particularly worthwhile, because reports of anterior PNPs continue to be inconsistent across sentence studies manipulating word expectancy (see Van Petten and Luka, 2006, for a review of earlier studies). It is also important to keep in mind that anterior PNP inconsistencies extend even to studies using the same materials and general experimental parameters, with the only difference being use of the VHF paradigm in one case but not the other (Federmeier et al., 2007; Wlotko and Federmeier, 2007, respectively). Therefore, if the potential factors examined below do play a role in determining when anterior PNPs are observed, their influence is likely to be modulated by the additional challenges imposed through lateralized sentence processing.

We begin by suggesting that stimulus factors may play a role in when the anterior PNP is elicited. Although the average sentence length for stimuli in Wlotko and Federmeier (2007) is similar to ours, critical sentences in the current study were preceded by context sentences to form mini discourses, if you will. This may

(*footnote continued*)
linearity that appears evident from plotting N400 mean amplitude as a function of cloze probability.

have afforded participant readers with a great deal more context and time to form richer and deeper contextual representations, which may have contributed to stronger pre-activations, and hence stronger violations when expected words were not received, in constraining contexts. Thus, we reason that richer contexts may have the effect of strengthening pre-activated information, to the point that it better withstands the difficulties of processing sentence continuations presented in the visual periphery.

Another factor possibly contributing to the presence or absence of anterior PNP effects with lateralized presentation is experimental task. In our study, half of the critical trials were followed by yes/no comprehension questions, whereas in Wlotko and Federmeier (2007, 2013) participants were informed ahead of time that they should "read the sentences for comprehension while keeping in mind that they would be asked questions about what they had read at the conclusion of the experiment." It is quite possible that this seemingly minor task difference could make a large difference in how participants approached the two studies. Kolk et al. (2003), for instance, found that when an acceptability judgment task was removed from a semantic illusion sentence study, a (posterior) P600-effect previously observed was greatly reduced. As somewhat of an aside, this also suggests that anterior and posterior late positivities may be related (see Coulson et al., 1998), as they may be subject to some of the same processing constraints.

One other factor possibly influencing the anterior PNP, may relate to the lateralized targets' word position within the sentence stimuli: our study used sentence-medial critical words and Wlotko and Federmeier (2007) used sentence-final words. ERP and eye-tracking effects on sentence final words have sometimes been identified as reflecting slightly different processing than sentence medial words (e.g., Osterhout, 1997; Rayner et al., 2000; Hagoort, 2003, where N400 effects were larger and more posteriorly-distributed in sentence final versus medial positions; however, see van Berkum et al., 1999, for a contrary finding, again, however for N400s, not PNPs). Osterhout (1997), in particular, noted that when comparing ERPs to syntactically vs. semantically anomalous words in sentence-final and -medial positions, a smaller percentage of individual participants exhibited P600s when critical words were at the ends of sentences. If the variability in such responses relates to some (still undefined) characteristic of individual participants, then this could potentially offer some explanation for the high degree of variability in observances of anterior PNPs across studies.

Finally, as we have previously suggested in a predictive processing study of older (60+ years) adults (DeLong et al., 2012), readers in the current study may have been sensitive to the cue value of the less expected indefinite articles preceding critical nouns, and in this way may have increased their expectancy for potential violations. In particular, the article cue value would have been strongest for the high constraint contexts, for which there is one highly expected noun continuation, and a phonologically-incompatible article would serve as a strong signal that the high cloze probability noun would not be received. Again, this additional information that informed prediction could be another explanation for why anterior PNPs were observed in the current study, but not in others.

6. Summary and conclusions

The following main points can be taken from the present study. First, both cerebral hemispheres exhibit similar sensitivity to cloze probability as an index of offline expectancy when processing more and less expected sentence continuations. This was true not only at the extreme ends of word expectancy, but also across the middle of the range, where previous work had indicated that the LH exhibited greater facilitation for weakly expected sentence continuations and the RH very little. So at least for some (but perhaps not all) sentence processing tasks, the two hemispheres respond in remarkably similar ways. These findings also offer one more bit of evidence against the RH being insensitive to message-level constraint, as RH N400 amplitude was modified by relatively subtle shifts in constraint values—except at the very weakest end of constraint—in a manner very similar to the LH. The second main point is that we show a LH bias in processing of sentential constraint violations. The ERP amplitude of the anterior PNP for RVF/LH processing was largest and thus most sensitive to strong violations of contextual constraint, although this response was a graded one. Without invoking a predictive language comprehension model, the LH constraint violation-sensitive anterior PNP finding is difficult to explain. Thus, when linguistic trajectories pre-activated via a potentially wide variety of possible associations (e.g., semantic relations, event knowledge, probabilistic co-occurrence, etc.) are disconfirmed by the input, additional or differential LH-biased processing seem to be called into play to update representations in working memory, inhibit or suppress highly predicted words, adjust learning based on information available in the local environment, or reallocate resources to adapt to a new mental model. Further targeted research is needed to adjudicate between these possibilities.

The late-occurring, LH-biased anterior ERP positivity associated with the consequences of not pre-activating information offers a complementary finding to (a) studies that have pointed to linguistic prediction based on observations of pre-activation effects *prior* to encountering critical word input (e.g., DeLong et al., 2005; Wicha et al., 2004; van Berkum et al., 2005; Szewczyk and Schriefers, 2013), and (b) those that have argued for more apparently predictive LH processing based on, for instance, N400 ERP effects *at* critical sentence continuations (e.g., Federmeier and Kutas, 1999a). Taken together, these results suggest a dynamic interplay of processes related (at a minimum) to neural pre-activation, access or (dis)confirmation of input, and subsequent contextual updating.

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