Event-related potentials show online influence of lexical biases on prosodic processing

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This event-related potential study examined how the human brain integrates (i) structural preferences, (ii) lexical biases, and (iii) prosodic information when listeners encounter ambiguous 'garden path' sentences. Data showed that in the absence of overt prosodic boundaries, verb-intrinsic transitivity biases influence parsing preferences (late closure) online, resulting in a larger P600 garden path effect for transitive than intransitive verbs. Surprisingly, this lexical effect was mediated by prosodic processing, a closure positive shift brain response was elicited in total absence of acoustic boundary markers for transitively biased sentences only. Our results suggest early interactive integration of hierarchically organized processes rather than purely independent effects of lexical and prosodic information. As a primacy of prosody would predict, overt speech boundaries overrode both

Introduction

Human language processing mechanisms are often confronted with sentences involving syntactic ambiguities, and sometimes a number of radically distinct types of information may facilitate (or impede) their resolution. How and when the brain uses and integrates various kinds of cues to generate a consistent interpretation is only poorly understood. Here, we present an event-related potential (ERP) study providing the first evidence of interactions between online prosodic phrasing and lexically stored probabilistic structural biases in the processing of auditorily presented closure ambiguities. For example, when the bracketed noun phrase (NP) in (1) is encountered in reading or speech, it can be syntactically integrated in two different ways: as the direct object of teaching [late closure, as in (1a)], or as the subject of the upcoming main clause [early closure, as in (1b)].

(1) When Mary was teaching [the lesson] …

> (a)   … the students paid attention

> (b)   … became clear.

In the absence of disambiguating cues (a comma after 'teaching', or in speech, a corresponding prosodic break), readers/listeners favor the late closure integration. Behavioral and eye-tracking data show processing difficulties

('garden path effects') when the disambiguating main clause information is encountered in continuations like (1b) but not in continuations like (1a). This is consistent with the existence of structural parsing heuristics that serve to pick the simplest possible syntactic analyses when ambiguities are encountered [1,2].

However, in addition to highly salient disambiguating cues (e.g. commas, prosodic breaks), other more subtle types of information have been argued to modulate such parsing preferences, including the relative probability with which particular verbs typically occur with direct objects (transitivity bias). Although the role of both prosody and transitivity bias in ambiguity resolution has been investigated separately, no prior study has addressed the question of whether (and how) these factors may interact in the online neural dynamics of spoken language comprehension. In one related eye-tracking study probing a very different type of structural ambiguity involving prepositional phrase attachment [e.g. 'Tickle/Choose the cow with the fork' (or: 'He observed the spy with binoculars/with a revolver')], Snedeker and Yuan [3] argued for independent effects of lexical and prosodic cues. This study, in contrast, was designed to examine the interaction of these factors as reflected in patterns of neurophysiological activity.

Prosody

Behavioral [4–11] and ERP [12,13] studies show that prosodic information guides listeners in the interpretation

of ambiguous sentences and can prevent garden path effects. Furthermore, the processing of prosodic units has been associated with a distinct ERP component – the closure positive shift (CPS) – which is a positive deflection near the midline elicited at prosodic boundaries. Importantly, this effect is not uniquely tied to actual pauses in speech – other cues signaling prosodic boundaries are sufficient (e.g. boundary acoustic cues, commas in silent reading [14]).

Transitivity bias

Several studies have suggested that transitivity bias has immediate effects on ambiguity processing [15–21]. In ERPs, such influences are detectable in terms of effects on the P600, a positive-going component with a posterior distribution taken to reflect syntactic processing difficulties and structural reanalysis after the parser has been 'led down the garden path' [19]. The P600 has been shown to be modulated by verbal transitivity bias. For example, in processing sentences such as 'The doctor believed/charged [the patient] was lying', the bracketed NP could initially be parsed as the direct object of 'believed/charged', resulting in a 'garden path effect' when the auxiliary 'was' is encountered (where a P600 should be elicited). However, Osterhout *et al.* [19] found that P600 effects arise only for transitively biased verbs ('charged'), and not verbs biased toward clausal complements ('believed').

About this study

We examined ERPs time-locked to the offset of ambiguous NPs (marked by ◀) in three types of auditorily presented sentences (Table 1a, b, and c), which were part of a larger study (also see Pauker *et al.*, under revision). On account of their prosodic breaks, condition A (late closure) and condition B (early closure) were unambiguous. In contrast, condition C, which must be resolved as an early closure structure, contained no such disambiguating prosodic break. In this study, we focus on a further manipulation designed to investigate the interaction of prosody and transitivity bias: half of the verbs occurring in the underlined positions (Table 1) were transitively biased, and the other half were intransitively biased.

Predictions

We expected to observe two types of ERP effects. First, the salient prosodic break (#) after the NP in condition A should yield a CPS, which should be absent for both conditions B and C (as these contain no posttarget breaks). Second, given the absence of a prosodic break in condition C, the disambiguating second verb (e.g. 'seemed') should elicit a garden path effect [i.e. a P600 relative to condition B]. Further, if there are no processing interactions between lexically stored structural biases and prosodic boundary information, then we should find uniform CPS effects within the transitive and intransitive bias subconditions. Finally, the absence of an explicit prosodic break in condition C may make it possible for lexical bias to gain influence in parsing decisions, resulting in a stronger garden path effect for the transitive than the intransitive bias conditions.

Methods

Participants

Twenty-six healthy right-handed native English-speaking undergraduates (13 women, age: 18–25, mean: 23, SD: 3.2) participated after giving informed consent. Six subjects (two women) were excluded from analyses because of excessive EEG artifacts.

Materials

Forty A/B sentence pairs (Table 1) were constructed with the first verb in each optionally transitive (i.e. consistent with both A/B continuations). Transitivity bias was calculated from corpus counts derived from Lapata *et al.* [22], separately summing token counts for each verb where it appeared with direct objects (transitive) and where it occurred without (intransitive). Transitivity bias was defined as the ratio of transitive over transitive and intransitive occurrences, yielding a low-to-high range from 0.15 to 0.90 (mean: 0.60, SD: 0.21). A median (0.65) split binned the verbs into two equal-sized groups: transitively biased (0.66–0.90, mean: 0.77, SD: 0.07) and intransitively biased (0.15–0.65, mean: 0.44, SD: 0.16).

Eighty A/B sentences were recorded with normal prosody, that is, with a boundary after the first verb ('playing') in B, and a boundary after the ambiguous NP ('the game') in A (marked by #, Table 1). Forty additional sentences for the garden path condition C were derived from A/B by digitally cross-splicing the initial portion of the A items with the final portion of the B items (illustrated by brackets in Table 1). A fourth condition, not relevant for the present inquiry, was generated by cross-splicing the initial portion of B and the final portion of A (see Pauker *et al.*, under revision), resulting in 160 experimental stimuli. Cue points marking words in each speech file allowed us to time-lock ERP analyses to the critical NP (at the '◀' marks in Table 1).

An additional 160 unrelated filler sentences were included to guard against participants developing processing strategies, consisting of half phrase–structure violations

Table 1 Example stimuli

(A) [While Billy was playing t]he game ◀ # the rules seemed simple	Late closure
(B) While Billy was playing # t[he game ◀ seemed simple]	Early closure
(C) [While Billy was playing t]he game ◀ seemed simple]	Garden path

(i) Bracketed [ ] portions of (A)/(B) conditions were digitally cross-spliced to generate the stimuli for (C); (ii) transitivity bias was manipulated for the underlined subordinate clause verbs (see Methods); (iii) ◀ marks the positions (offset of ambiguous noun phrase) to which event-related potential's analyzed below were time-locked; (iv) #, prosodic break.

(e.g. 'He hoped to *meal the enjoy' …) and half of the filler sentences were matched correct controls (e.g. 'He hoped to enjoy the meal' …). All sentence types were evenly distributed across four blocks of 80 trials intermixed in a pseudorandomized order. Eight experimental lists were created and evenly assigned across male/female participants.

Procedure
After 10 practice trials, participants listened to the sentences in a shielded, sound-attenuating chamber, and provided sentence-final acceptability judgments. Short breaks separated the four experimental blocks.

EEG recording
EEG was continuously recorded (500 Hz sampling rate; Neuroscan Synamps2 amplifier, Neuroscan-Compumedics, Charlotte, North Carolina, USA) from 19 cap-mounted Ag/AgCl electrodes (Electro-Cap International, Eaton, Ohio, USA) referenced to the right mastoid and placed according to the 10–20 system [23] (impedance $< 5\,k\Omega$). EOG was recorded from bipolar electrode arrays.

Data analysis
Acceptability judgment data were subjected to repeated-measures analyses of variance (ANOVAs) with factors conditions A–C and transitivity bias. EEG data were analyzed using EEProbe (ANT, Enschede, the Netherlands). Single subject averages were computed separately for six conditions (i.e. A/B/C × transitive bias/intransitive bias) after data preprocessing that included filtering (0.16–30 Hz band-pass), artifact rejection, and detrending. The number of trials surviving artifact rejection procedures did not significantly differ between the six conditions (range: 330–353 trials per condition). The detrending procedure subtracted slopes of very slow shifts in the DC recording, with relevant time-windows always including two trials (i.e. approximately 7 s).

Averages were based on all trials independent of the downstream behavioral response (note that ERPs did not differ between accepted and rejected trials for any effects reported below). Averages were computed for 1300 ms epochs beginning 100 ms before the offset of the target NPs (–100 to +100 baseline). ERP components were quantified by means of amplitude averages in five consecutive 200 ms windows from 150 to 1150 ms (i.e. 150–350, 350–550, 550–750, 750–950, and 950–1150). The first of these was used to test for CPS effects, and the latter four were used to quantify the P600 garden path effects.

Repeated-measures ANOVAs were run separately for midline (Fz/Cz/Pz) and 12 lateral electrodes (F3/4/7/8, C3/4, T3/4/5/6, P3/4, T5/6). ANOVAs for the 150–350 ms time-window (probing CPS effects) included the factor conditions A–C, and were carried out separately for the intransitive and transitive condition triples. The four subsequent 200 ms time-windows probing for P600 effects compared only the acoustically matched B/C conditions (i.e. for the four windows between 350 and 1150 ms), again separately for the intransitive-biased and transitive-biased conditions. Both midline and lateral analyses included the topographical factor anterior/posterior (frontal/central/posterior), and lateral analyses additionally included the factors, hemisphere (right vs. left) and laterality (medial vs. lateral). Greenhouse–Geisser corrections were used where applicable.

Results
Behavioral results
A condition main effect [$F(2,38) = 27.66$, $P < 0.0001$] indicated that acceptability in garden path condition C (53.5%) was lower than that in conditions A (87.5%) and B (87.2%), which did not differ ($F < 1$). A transitivity main effect [$F(1,19) = 11.95$, $P < 0.005$] reflected a higher overall acceptability of sentences containing intransitively versus transitively biased verbs, especially in condition C (56.4 vs. 50.5%), but no interaction was found. Across verbs, response times for accepted trials were longer in condition C (956 ms) than in conditions A (680 ms) and B (701 ms) [$F(2,36) = 18.88$, $P < 0.0001$], again reflecting the garden path effect. Finally, participants needed less time to reject trials in transitively biased condition C (868 ms) than intransitively biased condition C (987 ms) [$F(1,17) = 10.98$; $P < 0.004$], suggesting that transitivity biases resulted in more severe garden path effects.

Event-related potentials
Grand average ERP waves for conditions A–C are plotted separately for the intransitive-biased/transitive-biased conditions in Fig. 1 alongside voltage maps showing mean amplitudes of CPS difference waves. Results of CPS analyses are shown in Table 2.

Both the predicted CPS and P600 effects were obtained, and there was an additional quite striking unexpected finding. First, the intransitively biased conditions yielded the expected CPS (150–350 ms) for the condition A relative to conditions B and C. Significant effects in the global ANOVA for this time-window were traceable in follow-up analyses to A/B and A/C differences (Table 2). This CPS effect had a frontocentral maximum (see the A/B and A/C difference maps in Fig. 1), as shown by further interactions with laterality and anterior/posterior (Table 2). In contrast, the transitively biased conditions showed statistically indistinguishable CPS-like positive shifts for conditions A and C relative to condition B (Fig. 1; Table 2). This finding is surprising given that the condition C did not contain any overt prosodic boundary information. Although earlier work has shown that various factors can induce subvocal prosodic phrasing (and thus CPS effects) in silent reading [14,24], to the best of our

Fig. 1
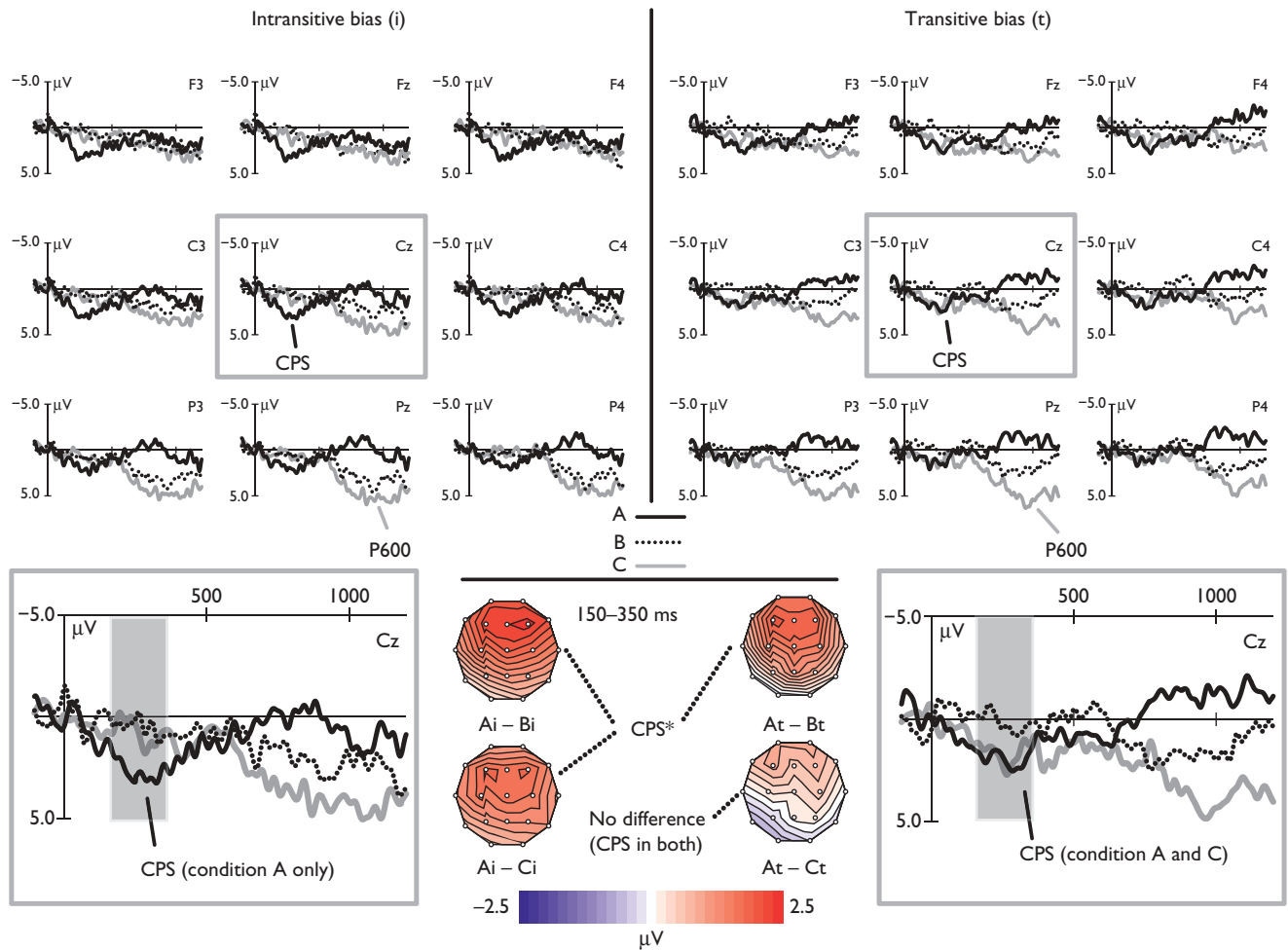
Grand average waveforms and voltage maps for sentence types A–C containing intransitively biased (i)/(left) and transitively biased (t)/(right) subordinate clause verbs. Waveforms are time-locked to the offset of the critical ambiguous noun phrase (from − 100 to 1200 ms). Voltage maps show closure positive shift (CPS) (150–350 ms) differences for A/B and A/C for both intransitive-biased (Ai/Bi/Ci) and transitive-biased (At/Bt/Ct) conditions.

knowledge, none has ever suggested that nonprosodic information might elicit such effects in the processing of connected speech.

As to the P600 for the intransitively biased conditions, although B/C × laterality interactions were obtained in the two final time-windows [750–950 ms: $F_{(1,19)} = 6.12$, $P < 0.05$; 950–1150 ms: $F_{(1,19)} = 8.07$, $P < 0.05$], there were no significant B/C effects on the midline or in follow-up analyses conducted for lateral/medial electrodes separately.

In contrast, the transitively biased comparison in the three final time-windows yielded interactions of B/C with both anterior/posterior [550–750 ms: $F_{(2,38)} = 3.94$, $P < 0.05$; 750–950 ms: $F_{(2,38)} = 5.28$, $P < 0.05$] and laterality [950–1150 ms: $F_{(1,19)} = 10.03$, $P < 0.01$]. In addition, here, there were also B/C × anterior/posterior interactions on the midline [750–950 ms: $F_{(2,38)} = 5.13$,

$P < 0.05$; 950–1150 ms: $F_{(2,38)} = 5.10$, $P < 0.05$]. These interactions reflected the emergence of a broadly posterior P600 garden path effect (Fig. 1), which in the final time-window, showed larger amplitudes closer than further from the midline.

Discussion

First, our data show that in the absence of overt prosodic boundaries (condition C), the listener's parser relies on the same heuristics that lead to garden path effects in reading data [25].

However, transitivity bias has a clear impact, reflected by both a larger P600 deflection (replicating reading findings [19]) and by shorter rejection times.

Second, the influence of transitivity bias on the severity of the garden path effect may be mediated by prosodic phrasing. CPS effects were observed not only for the

Table 2 Results of CPS analyses (150–350 ms)

	Global ANOVA	Pair-wise follow-up	
Intransitive			
Condition (A/B/C)	6.05***	AB	9.21***
C × L	2.99*	AB × L	5.22**
C × AP	4.85***	AB × AP	7.81***
C × H	–	AC	10.73***
C × L × AP	–	AC × L	4.57**
C × L × H	–	AC × AP	–
C × AP × H	–	BC	–
C × L × AP × H	–	BC × L	–
		BC × AP	–
Midline			
C	5.93***	AB	8.84***
C × AP	–	AC	11.51***
		BC	–
Transitive			
Condition (A/B/C)	–	AB	3.66*
C × L	5.96***	AB × L	10.07***
C × AP	2.68*	AB × AP	3.78*
C × H	–	AC	–
C × L × AP	–	AC × L	–
C × L × H	–	AC × AP	–
C × AP × H	2.34*	BC	–
C × L × AP × H	–	BC × L	9.07***
		BC × AP	–
Midline			
C	2.91**	AB	5.98**
C × AP	–	AC BC	4.09**

ANOVA, analysis of variance; AP, anterior/posterior; CPS, closure positive shift;
H, hemisphere; L, laterality.
*$P < 0.10$.
**$P < 0.05$.
***$P < 0.01$.

condition A containing a prosodic break, but also for the transitively biased (but not the intransitively biased) condition C. It was already known that CPS effects are elicited in the absence of overt acoustic prosodic information, as they manifest even in silent reading in connection with the processing of commas [14,24]. What is new and striking about the present finding is that a prosodic boundary was apparently established because both the initial parsing preference (for late closure) and the lexical bias (for transitivity) strongly supported a syntactic boundary that usually coincides with a prosodic boundary. The combined evidence was sufficient to drive the brain systems in charge of prosodic constituency to impose a boundary after the target NP despite the absence of any boundary markers in the speech signal. Moreover, this processing seems to take place with a time course that yields a CPS profile that is statistically indistinguishable from the effects elicited by stimuli that actually contain overt prosodic breaks (condition A). Finally, the absence of any such CPS effect in the intransitively biased condition C shows that the structural bias for late closure is, on its own, insufficient to establish the corresponding prosodic constituency.

Elsewhere [12], reduced CPS amplitude effects have been shown at overt prosodic boundaries, if preceding discourse contexts allowed listeners to anticipate the boundary based on syntactic expectancies. The findings here are complementary: probabilistic lexicosyntactic cooccurrence information can initiate prosodic phrasing in the absence of relevant acoustic cues in the speech stream. Combined, both studies strongly suggest an immediate interactive mapping of syntactic and prosodic representations.

Third and finally, our data also show that overt prosodic boundaries provide the strongest cues for parsing decisions and completely override both initial structural preferences (such as the late closure principle) and lexical biases. Thus, the early boundary in condition A prevented any garden path effect, irrespective of verb biases.

Conclusion
Our data suggest a hierarchical order of cues that listeners rely on when processing structurally ambiguous sentences. Overt prosodic boundaries elicit CPS responses and provide the dominant cue that overrides competing information and can reliably prevent misunderstandings (condition A). In absence of speech boundaries, listeners follow the same parsing principles as readers (e.g. the late closure principle) that can cause P600 garden path effects (condition C). Lexical transitivity biases modulate parsing preferences. When they support the initial preference, the accumulated evidence may be sufficient to initiate prosodic phrasing (CPS components in absence of acoustic cues), which then affects the strength of garden path effects. Thus, at least in closure ambiguities, the human brain seems to integrate various types of information online and interactively, rather than independently.

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