Connectionist Language Processing

Lecture 12: Modeling the Electrophysiology of Language II

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Event-Related Potentials (ERPs)
Event-Related Potentials (ERPs)
Event-Related Potentials (ERPs)
The standard view

N400 is semantic integration

P600 is syntactic processing
The new view

N400 is semantic integration $\rightarrow$ lexical retrieval

P600 is syntactic processing $\rightarrow$ semantic integration
N400 — semantic integration

He spread his warm bread with socks

He spread his warm bread with butter

Kutas & Hillyard (1980) Science
The spoilt child *throw* the toys on the floor

The spoilt child *throws* the toys on the floor
Puzzle — the ‘semantic’-P600

De speer heeft de atleten geworpen  
‘The javelin has the athletes thrown’

De speer werd door de atleten geworpen  
‘The javelin was by the athletes thrown’
Puzzle — the ‘semantic’-P600

De speer heeft de atleten geworpen
‘The javelin has the athletesthrown’

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Expected: N400-effect, no P600-effect
Puzzle — the ‘semantic’-P600

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Observed: P600-effect, no N400-effect
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Observed: P600-effect, no N400-effect

Solution: people were tricked into a ‘semantic illusion’
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Observed: P600-effect, no N400-effect

Solution: people were tricked into a ‘semantic illusion’
Implication: independent semantic analysis stream
Multi-stream models

De speer heeft de atleten geworpen
‘The javelin has the athletes thrown’
Multi-stream models

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**semantic analyzer**
javelin + athletes + thrown

**structure-driven analyzer**
[S [NP the javelin] [VP ...]]
Multi-stream models

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“the athletes have thrown the javelin”

“the javelin has thrown the athletes”

?? who/what is doing what to whom/what ??

no N400

P600
Multi-stream models

Semantic Attraction (SA)
(Kim and Osterhout, 2005)

Monitoring Theory (MT)
(Van Herten et al., 2005, 2006)

Continued Combinatory Analysis (CCA)
(Kuperberg, 2007)

ext. Argument Dependency Model (eADM)
(Bornkessel-Schlesewsky and Schlesewsky, 2008)

Processing Competition (PC)
(Hagoort et al., 2009)
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## Multi-stream models (cont’d)

<table>
<thead>
<tr>
<th>Item</th>
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<th>MT</th>
<th>CCA</th>
<th>eADM</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoeks et al. (2004)</td>
<td></td>
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<tr>
<td>De speer werd door de atleten geworpen</td>
<td>P6</td>
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<td>P6</td>
<td>P6</td>
<td>N4/P6</td>
</tr>
<tr>
<td>De speer heeft de atleten geworpen</td>
<td>P6*</td>
<td></td>
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<td>De speer werd door de atleten opgesomd</td>
<td>N4/P6</td>
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<tr>
<td>The hearty meal was devoured…</td>
<td>P6</td>
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<td>The hearty meal was devouring…</td>
<td>N4/(P6)*</td>
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<tr>
<td>The dusty tabletops were devouring…</td>
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<tr>
<td>De stroper die op de vos joeg…</td>
<td>—</td>
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<tr>
<td>For breakfast the boys would eat…</td>
<td>N4</td>
<td>N4</td>
<td>N4</td>
<td>N4</td>
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<td>N4</td>
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<tr>
<td>For breakfast the boys would watch…</td>
<td>P6</td>
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<td>For breakfast the eggs would eat…</td>
<td>(N4)/P6</td>
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<td>Fred eet een boterham…</td>
<td>N4</td>
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<td>N4</td>
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<td>Fred eet een restaurant…</td>
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<tr>
<td>Prior context…</td>
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<td>Next, the woman told the tourist…</td>
<td>P6</td>
<td>N4</td>
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<td>Next, the woman told the suitcase…</td>
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</table>
Multi-stream models (cont’d)

Q: Architectural deficit? Or wrong interpretations of N400 and P600?
The Retrieval hypothesis

N400 is retrieval of lexical information from memory, which is facilitated through lexical and contextual priming
N400 as lexical retrieval

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The javelin has the athletes thrown
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N400-effect

No N400-effect
N400 as lexical retrieval

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Q: Now what about semantic integration?
P600 as semantic integration

The MRC hypothesis

P600 is a family of late positivities that reflect the *word-by-word* construction, reorganization, or updating of a mental representation of what is being communicated (and MRC)
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MRC (re)construction is effortful—P600 amplitude is increased—when:
— new discourse entities require accommodation (referent introduction)
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— the interpretation conflicts with world knowledge (‘semantic illusions’)

Implication: biphasic N400/P600 “Retrieval-Integration” cycles
Aligning Time and Place
Where does all of this leave us?

> A single-stream account of the N400 and the P600 in language comprehension
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> A single-stream account of the N400 and the P600 in language comprehension

> But, like the other models, only a conceptual ‘box-and-arrow’ model …
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> But, like the other models, only a conceptual ‘box-and-arrow’ model …

> … and conceptual ‘box-and-arrow’ models suck (!)… big time (!!!); they lack serious predictive power, as predictions are subjective and flexible
Where does all of this leave us?

> A single-stream account of the N400 and the P600 in language comprehension

> But, like the other models, only a conceptual ‘box-and-arrow’ model …

> … and conceptual ‘box-and-arrow’ models suck (!)… big time (!!!); they lack serious predictive power, as predictions are subjective and flexible

> Solution: Implement mathematically explicit (neuro)computational models that generate quantitative predictions
What makes a good computational model?

> Model comprehension and not just word prediction or syntactic parsing
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> **Model comprehension** and not just word prediction or syntactic parsing

> **Model the right level of granularity**: index scalp-recorded summations of post-synaptic potentials in large neural populations
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> **N400 and P600 estimates should emerge from processing behaviour**, the model should not be explicitly trained to produce these estimates
What makes a good computational model?

- Model comprehension and not just word prediction or syntactic parsing

- Model the right level of granularity: index scalp-recorded summations of post-synaptic potentials in large neural populations

- N400 and P600 estimates should emerge from processing behaviour, the model should not be explicitly trained to produce these estimates

- Account for signature processing phenomena: ERPs to semantic anomaly, semantic expectancy, syntactic violations, garden-paths, reversal anomalies
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> **N400 and P600 estimates should emerge from processing behaviour**, the model should not be explicitly trained to produce these estimates

> **Account for signature processing phenomena**: ERPs to semantic anomaly, semantic expectancy, syntactic violations, garden-paths, reversal anomalies

We present such a computational model that implements the **Retrieval** view on the N400, and the **Integration** view on the P600 (cf. Brouwer et al., 2012)
Model Architecture

integration_output (300)

integration (250)

retrieval_output (100)

retrieval (150)

integration_context (250)

input (48)

[~N400]

[~P600]
Model Architecture

integration_output
(300)

integration
(250)

retrieval_output
(100)

retrieval
(150)

integration_context
(250)

input
(48)

retrieval system

~N400

~P600
Model Architecture

integration context
(250)

integration_output
(300)

integration
(250)

retrieval output
(100)

retrieval
(150)

integration system

[~N400]

[~P600]

input
(48)
Model Architecture

context established at time step $t-1$

word perceived at time step $t$
context established at time step \( t-1 \)

word perceived at time step \( t \)

feature-based word meaning representation

retrieval: provided word and context, activate word meaning

\[ N400 = \Delta \text{ activity from } t-1 \text{ to } t \]
Model Architecture

Context established at time step $t-1$

Word perceived at time step $t$

Integration context

Integration output

Retrieval output

Retrieval

Integration

Input

Utterance interpretation

Integration: integrate word meaning with context to update utterance interpretation

$P600 = \Delta$ activity from $t-1$ to $t$

Feature-based word meaning representation

~N400

~P600
Provide context for word at $t+1$

Context established at time step $t-1$
> Taught to comprehend a wide range of structures, allowing us to test it on a range of contrasts analogous to signature processing phenomena and their related ERP findings.
N400 to Semantic Anomaly

a man drinks rugby / beer  
(N400: rugby > beer)
N400 to Semantic Anomaly

*a man drinks rugby / beer*  
(N400: rugby > beer)

![Diagram showing N400 estimates for 'rugby' and 'beer'](image_url)

* Error bars show standard errors
N400 to Anomaly versus Expectancy

men eat an/a automobile / salad / steak  
(N400: automobile > salad > steak)  
(* in the model’s world, men prefer steak over salad)
N400 to Anomaly versus Expectancy

men eat an/a automobile / salad / steak

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N400 to Anomaly versus Expectancy

men eat an/a automobile / salad / steak

(N400: automobile > salad > steak)

(* in the model’s world, men prefer steak over salad)

Q: But what about signature P600 modulations?

Syntactic Violations

a man were / was [...]

(N400: were = was | P600: were > was)
Syntactic Violations

a man were / was [...]

(N400: were = was | P600: were > was)
Syntactic Violations

a man \textit{were} / \textit{was} [...] (N400: \textit{were} = \textit{was} | P600: \textit{were} > \textit{was})

N400 estimates

P600 estimates

Connectionist Language Processing — Crocker & Brouwer

cf. Molinaro et al. (2008), \textit{Cognition}
cf. Hagoort et al. (1993), \textit{LCP}
Garden-paths

a man admired eats [...]  
a man that was admired eats [...]  
(N400: red. = unred. | P600: red. > unred.)
Garden-paths

a man admired *eats* [...]  
a man *that was* admired *eats* [...]  

(N400: *red.* = *unred.* | P600: *red.* > *unred.*)
Garden-paths

a man admired *eats* [...] a man *that was* admired *eats* [...] 

(N400: red. = unred. | P600: red. > unred.)

![Graph showing N400 and P600 estimates for control and target conditions.](image-url)
Semantic Anomalies revisited

a man drinks rugby / beer

(P600: rugby > beer)

cf. Kutas & Hillyard (1980), Science
Semantic Anomalies revisited

a man drinks rugby / beer

(P600: rugby > beer)

cf. Kutas & Hillyard (1980), Science
Semantic Anomalies revisited

Q: What about reversal anomalies (i.e., the “Semantic P600”-effect)?

a man drinks rugby / beer

(P600: rugby > beer)

cf. Kutas & Hillyard (1980), Science
Reversal Anomalies

a steak was eating / eaten [...]  (N400: eating = eaten | P600: eating > eaten)
Reversal Anomalies

a steak was eating / eaten […] (N400: eating = eaten | P600: eating > eaten)
Reversal Anomalies

A steak was eating / eaten [...] (N400: eating = eaten | P600: eating > eaten)

N400 estimates

P600 estimates

cf. Kim & Osterhout (2005), JML
Conclusion

> We have presented a computational model of language comprehension
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> We have proposed *explicit* and *scalable* linking hypotheses to electrophysiology:

\[
\text{N400} \rightarrow \text{Retrieval} \quad \text{P600} \rightarrow \text{Integration}
\]
We have presented a computational model of language comprehension.

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A single simulation shows that the model accounts for signature ERP findings:
Conclusion

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> We have proposed explicit and scalable linking hypotheses to electrophysiology:

\[ N400 \rightarrow \text{Retrieval} \quad P600 \rightarrow \text{Integration} \]

> A single simulation shows that the model accounts for signature ERP findings:

| Semantic Anomaly | a man drinks rugby / beer | N400 / P600 | ✓ |
Conclusion

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<table>
<thead>
<tr>
<th>Semantic Anomaly</th>
<th>a man drinks rugby / beer</th>
<th>N400 / P600</th>
<th>✓</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semantic Expectancy</td>
<td>men eat an/a automobile / salad / steak</td>
<td>graded N400</td>
<td>✓</td>
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<table>
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<th>ERP Pattern</th>
<th>Match</th>
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<tr>
<td>Syntactic Violations</td>
<td>a man <em>were</em> / <em>was</em> [...]</td>
<td>P600</td>
<td>✓</td>
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<table>
<thead>
<tr>
<th>Type of Violation</th>
<th>Example Sentence</th>
<th>ERP Response</th>
</tr>
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<tbody>
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<td>Semantic Anomaly</td>
<td>a man drinks rugby / beer</td>
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<td>men eat an/a automobile / salad / steak</td>
<td>graded N400</td>
</tr>
<tr>
<td>Syntactic Violations</td>
<td>a man were / was […]</td>
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<td>a man [that was] admired eats […]</td>
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</tr>
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</table>
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<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>N400 / P600</th>
<th>Verified</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Semantic Anomaly</strong></td>
<td>a man drinks <em>rugby</em> / <em>beer</em></td>
<td>N400 / P600</td>
<td>✓</td>
</tr>
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<tr>
<td><strong>Reversal Anomalies</strong></td>
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> A single simulation shows that the model accounts for signature ERP findings:
Conclusion

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\[
\begin{align*}
\text{N400} & \rightarrow \text{Retrieval} & \text{P600} & \rightarrow \text{Integration}
\end{align*}
\]

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  N400 / P600 ✓

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> A comprehensive computational model that can be scaled to more phenomena
Directions for future work

*Proximate goals:*

> **Temporal dynamics:** model how N400 and P600 amplitude develop over time
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> **Pragmatics:** account for the expanding pool of pragmatically-induced P600-effects (e.g., irony, topic-shift, missing information, bridging inferences)