T.39.03

# Dissociating Syntactic Operations via Composition Count

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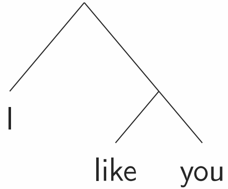
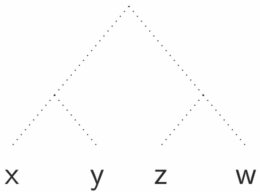
# Motivation

- Natural language has **syntactic structures** (Chomsky, 1957).
    - which are essential for computing the meaning (Montague, 1970; Heim and Kratzer, 1998).
- Syntactic structures are built in online sentence processing (e.g., Roark et al., 2009; Fossum and Levy, 2012; Brennan et al., 2016; Nelson et al., 2017; Hale et al., 2018).
- Question:
  **How do we build the structures?**

... I like you ... ⇒



- (*bottom-up* parsing)



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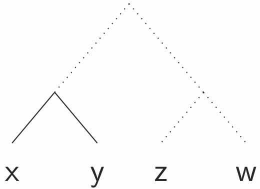

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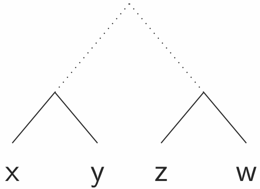

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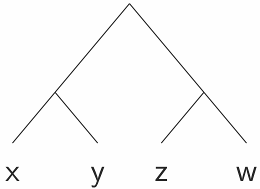
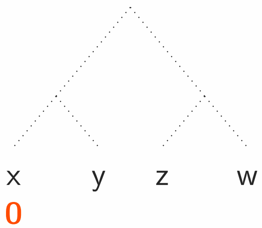


## Node Count

A complexity metric that counts the number of *syntactic **nodes*** representing syntactic structures.

- Comp Psycholings has employed this metric (e.g., Brennan et al., 2016; Brennan and Pylkkänen, 2017; Nelson et al., 2017; Stanojević et al., 2023).



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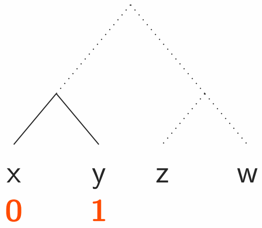

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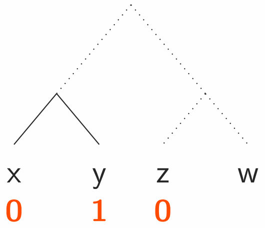

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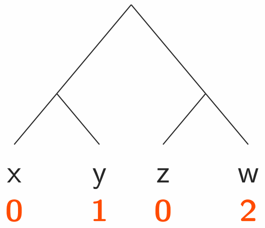

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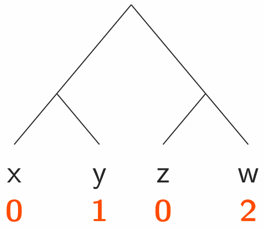
- Different from *expectation*-based metrics (e.g., Hale, 2001; Levy, 2008) and *memory*-based metrics (e.g., Gibson, 2000; Lewis and Vasishth, 2005).



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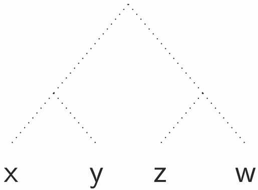
- Node Count does **not** dissociate distinct syntactic *operations* deriving those syntactic structures.



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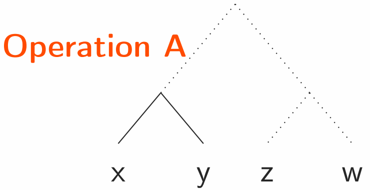

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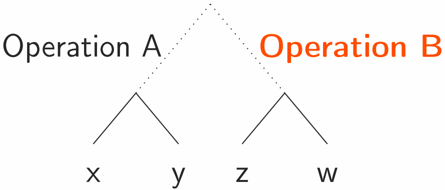

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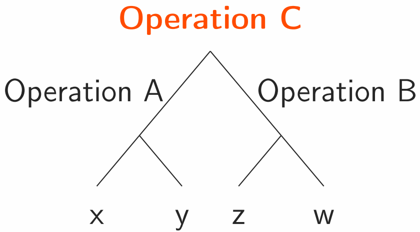

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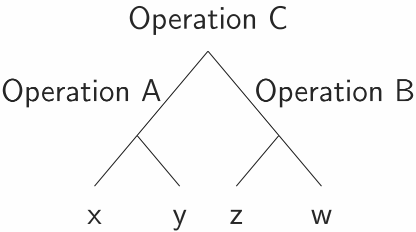
- How much processing cost does each *syntactic operation* induce?



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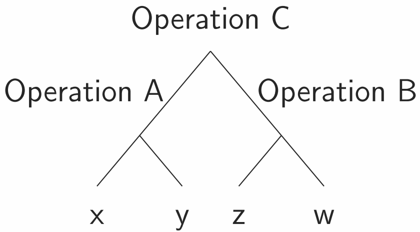
$\Longrightarrow$ **Composition Count**



# In our study

## Node Count

A complexity metric that counts the number of *syntactic **nodes*** representing syntactic structures.

$\Downarrow$

## Composition Count

A complexity metric that counts the number of *syntactic **operations*** deriving syntactic structures.

- To understand the computational system of human sentence processing from the *derivational*, not *representational*, perspective.

# In our study

- We employ Combinatory Categorial Grammar (CCG; Steedman, 2000) because
  - equipped with **multiple syntactic operations**.
  - its Node Count can predict processing costs in English (Stanojević et al., 2023).
- We investigate
  1. how much **distinct** syntactic operations of CCG contribute to predicting human reading times (RT).
  2. whether the same holds in both head-initial (**English**) and head-final (**Japanese**) languages.

# Combinatory Categorial Grammar (CCG)

- CCG is equipped with multiple syntactic operations with distinct syntactic and semantic properties.
  - We used the following **three** main syntactic operations:
- FC and TR are introduced based on linguistic motivation, and they are also psycholinguistically valid as they enable incremental parsing.

**Function Application (FA)**

$$\begin{cases} X/Y \quad Y \Longrightarrow X \\ Y \quad X\backslash Y \Longrightarrow X \end{cases}$$

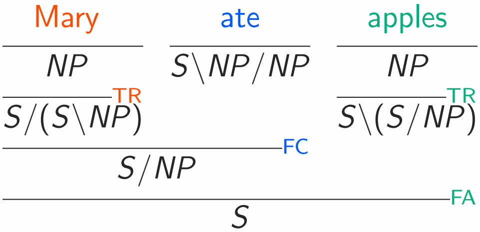
**Function Composition (FC)**

$$\begin{cases} X/Y \quad Y/Z \Longrightarrow X/Z \\ Y\backslash Z \quad X\backslash Y \Longrightarrow X\backslash Z \end{cases}$$

**Type Raising (TR)**

$$\begin{cases} X \Longrightarrow T/(T\backslash X) \\ X \Longrightarrow T\backslash(T/X) \end{cases}$$

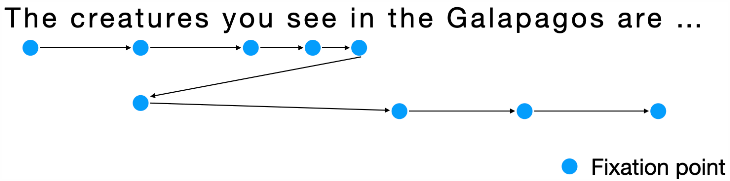
# Composition Count




| | | Mary | ate | apples |
|---|---|---|---|---|
| Composition Count | *FA* | 0 | 0 | 1 |
| | *FC* | 0 | 1 | 0 |
| | *TR* | 1 | 0 | 1 |
| | *Node Count* | 1 | 1 | 2 |

# Reading time data

**English** The Dundee corpus (Kennedy et al., 2003); 10 English native speakers
**Japanese** BCCWJ-EyeTrack (Asahara et al., 2016); 24 Japanese native speakers



# Statistical analysis

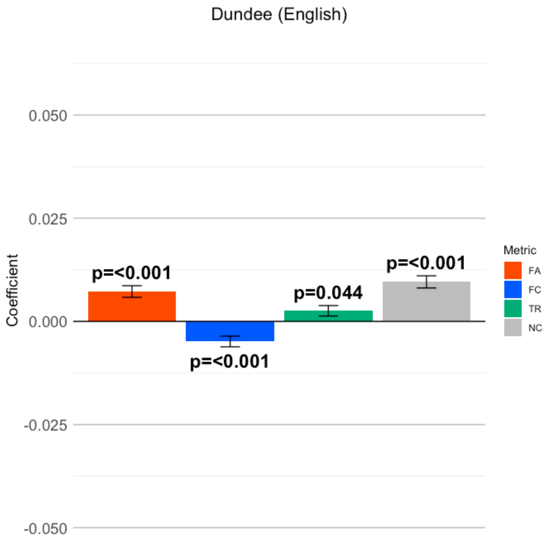
- We used a *linear mixed-effects model* (Baayen et al., 2008).
  - constructed **four** separate models

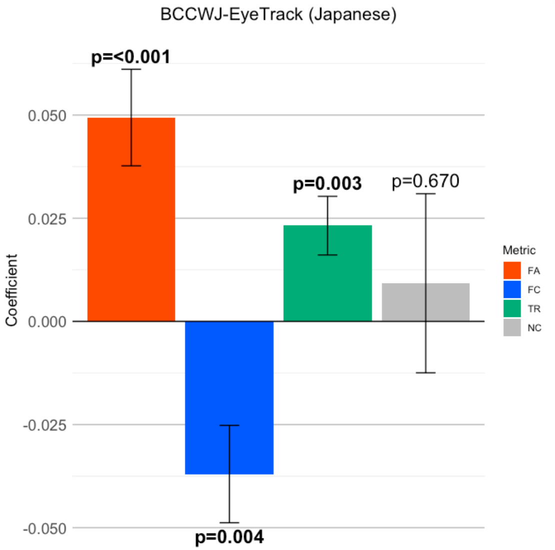
1. Baseline + FA
2. Baseline + FC
3. Baseline + TR
4. Baseline + Node Count

⇒ estimated their **coefficients**

$$\begin{aligned}\texttt{log(RT)} \sim\ & \texttt{dependent} + \texttt{wlen} + \texttt{num\_of\_word} + \texttt{freq} + \texttt{prev\_freq} \\ & + \texttt{surp} + \texttt{phraseN} + \texttt{lineN} + \texttt{screenN} + \texttt{prev\_is\_fixed} \\ & + \texttt{(1|article)} + \texttt{(1|subject)}\end{aligned}$$

# Results


Dundee (English)
Coefficient
0.050
0.025
0.000
-0.025
-0.050
p=<0.001
p=<0.001
p=0.044
p=<0.001
Metric
FA
FC
TR
NC


BCCWJ-EyeTrack (Japanese)
Coefficient
0.050
0.025
0.000
-0.025
-0.050
p=<0.001
p=0.004
p=0.003
p=0.670
Metric
FA
FC
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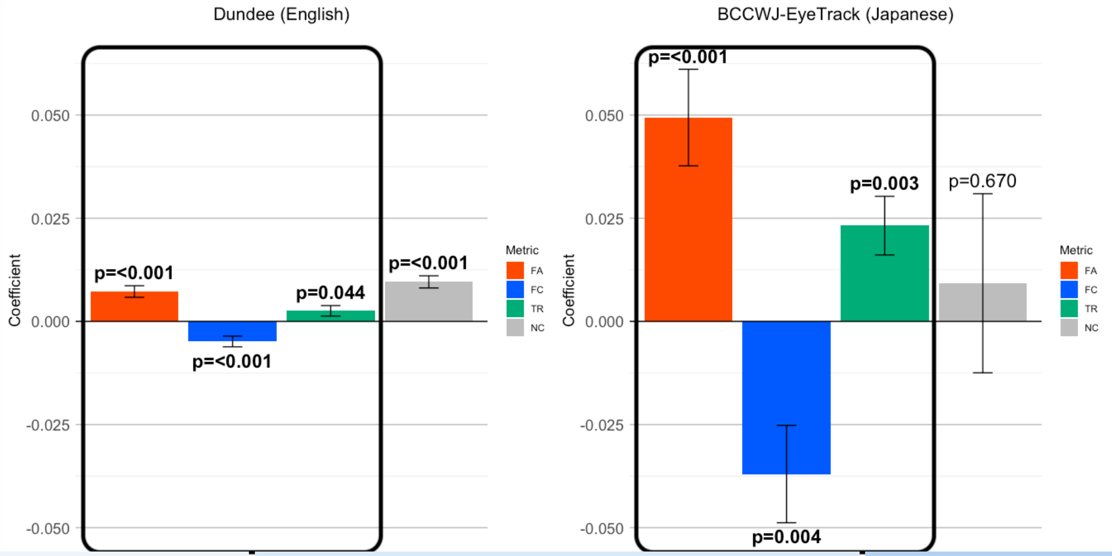
NC

# Results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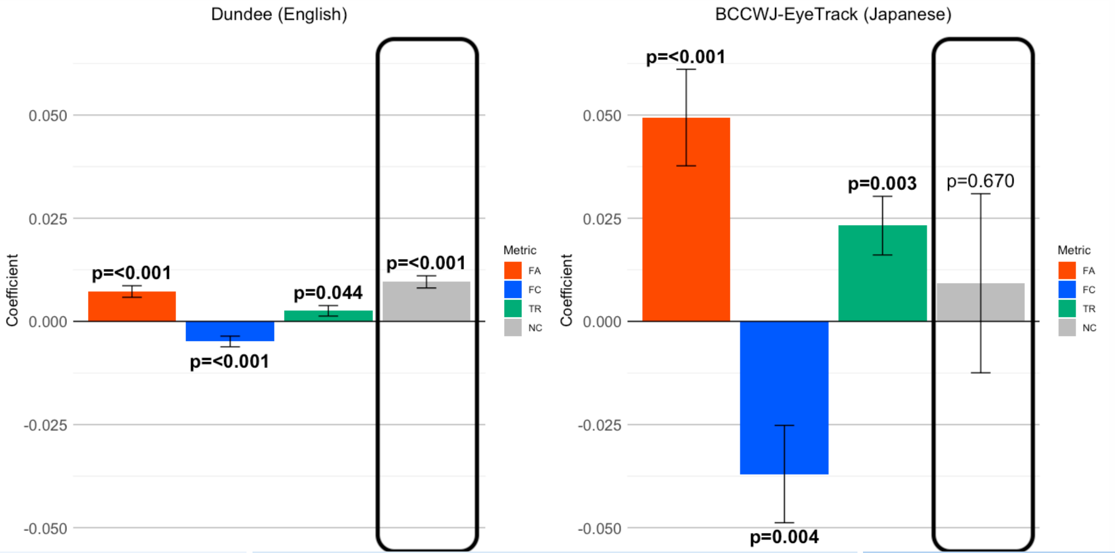

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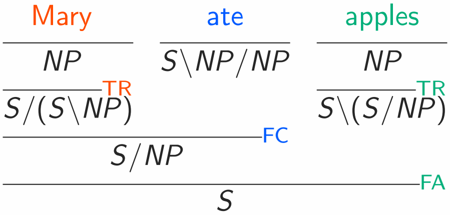
# Discussion

- All Composition Counts significantly predict human reading times in both English and Japanese
  - suggesting that *the operations theoretically licensed in linguistics* are **directly** applicable to human sentence processing.
  - Node Count is not a robust predictor.
- The relative magnitudes were found to be consistent across both languages.
- Owing to the Composition Counts, we have been able to detect **the processing costs** of each syntactic operation.



# Discussion

- FC exhibited negative effects, while FA/TR are positive.
    - Semantically, FC is more complex than FA.
    - Theoretical computational complexity may not necessarily translate into higher cognitive processing costs.
    - But the distinctions of grammatical rules may be preserved as distinctions of parsing operations, as Berwick and Weinberg (1983) pointed out.

# Conclusion

- We introduced **Composition Count**.
  - FA/TR and FC exhibited positive and negative effects, respectively, with the relative magnitude of the effects being FA $>$ TR $>$ FC.
  - In contrast, Node Count turned out not to be robust crosslinguistically.
- Suggests the importance of focusing on **distinct syntactic operations**, rather than on *syntactic represention*s.

# Acknowledgments


- We thank Shinnosuke Isono for his helpful feedback.
- We also thank the three anonymous reviewers for their insightful comments.
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