



Original Articles

Who did what? A causal role for cognitive control in thematic role assignment during sentence comprehension

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ABSTRACT

Thematic role assignment – generally, figuring out who did what to whom – is a critical component of sentence comprehension, which is influenced by both syntactic and semantic cues. Conflict between these cues can result in temporary consideration of multiple incompatible interpretations during real-time sentence processing. We tested whether the resolution of syntax-semantics conflict can be expedited by the online engagement of cognitive control processes that are routinely used to regulate behavior across domains. In this study, cognitive control deployment from a previous Stroop trial influenced eye movements during subsequent sentence comprehension. Specifically, when syntactic and semantic cues competed for influence on interpretation, dynamic cognitive control engagement led to (a) fewer overall looks to a picture illustrating the competing but incorrect interpretation (Experiment 1), or (b) steeper growth in looks to a picture illustrating the correct interpretation (Experiment 2). Thus, prior cognitive control engagement facilitated the resolution of syntax-semantics conflict by biasing processing towards the intended analysis. This conflict adaptation effect demonstrates a causal connection between cognitive control and real-time thematic role assignment. Broader patterns demonstrated that prior cognitive control engagement also modulated sentence processing irrespective of the presence of conflict, reflecting increased integration of newly arriving cues with prior sentential content. Together, the results suggest that cognitive control helps listeners determine correct event roles during real-time comprehension.

1. Introduction

An important aspect of sentence comprehension involves thematic role assignment, namely understanding the roles that various participants play in an event. For example, when hearing a sentence such as “*The boy chased the girl!*”, the listener must determine that the boy was the one who did the pursuing and the girl was the one who did the fleeing, not the other way around. Syntactic structure is an influential cue that can guide comprehension of who did what to whom: It helps determine which noun phrase in the sentence is the Agent of the action (the doer) and which is the Patient (the affected entity). However, structure is just one cue that informs the parser. Semantic knowledge about the sentential nouns—e.g., whether they are animate like boys and girls—and the real-world events mentioned in the sentence—e.g., whether the nouns are more plausibly Agents or Patients of a particular transitive verb—can also influence interpretation (hence, “*Man bites dog*” is surprising and headline-worthy). When syntactic and semantic

cues compete for influence, there are dramatic effects on comprehension, including uncertainty about who did what to whom and the need to resolve competing thematic role assignments (see e.g., Ferreira, 2003; Sturt, 2007). Here, we test whether cognitive control engagement can facilitate such resolution.

Semantic constraints are reliable evidential cues to Agent- and Patienthood that can rapidly direct comprehenders’ moment-by-moment interpretations. Consider 1a and 1b:

1a: The defendant examined by the lawyer turned out to be unreliable.

1b: The evidence examined by the lawyer turned out to be unreliable.

Both sentences have passive structures: The first noun (defendant, evidence) is the Patient of the transitive verb “*examined*” rather than its Agent, and the second noun (lawyer) is the Agent. But up until the word

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“by”, the input is syntactically ambiguous, consistent with both the active and passive constructions. However, a key difference between 1a and 1b is the thematic fit of defendants and evidence as probable perpetrators of the described action: Semantically, “defendant” is a plausible Agent (it is animate) whereas “evidence” is not. Several studies have shown that upon encountering “by the lawyer”, processing is slower in sentences like 1a than 1b, suggesting that readers experience temporary conflict in the case of “The defendant...” because the semantic cue (animacy) competes with the syntax. By contrast, in 1b, “evidence” is inanimate and thus an unlikely Agent but liable Patient. Here, the semantic cue cooperates with the syntax, allowing processing to converge earlier on the Patient interpretation (e.g., Pearlmutter & MacDonald, 1992; Trueswell, Tanenhaus, & Garnsey, 1994). While the relative weighting of semantic and morphosyntactic cues for comprehension might vary among languages (Bates & MacWhinney, 1989), current evidence suggests that animacy can be a relevant cue for sentence interpretation even in morphologically rich languages that are different from English (e.g., Russian: Stoops, Luke, & Christianson, 2014; Turkish: Demiral, Schlesewsky, & Bornkessel-Schlesewsky, 2008).

Beyond animacy, a number of studies have shown that semantic plausibility and world knowledge about events can affect, even shape, online as well as offline interpretation (Altmann & Kamide, 2007; Christianson, Hollingworth, Halliwell, & Ferreira, 2001; Christianson, Luke, & Ferreira, 2010; Ferreira, 2003; Garnsey, Pearlmutter, Myers, & Lotocky, 1997; Kamide, Altmann, & Haywood, 2003; Kamide, Scheepers, & Altmann, 2003; Kim & Osterhout, 2005; Knoeferle, Crocker, Scheepers, & Pickering, 2005; Malyutina & den Ouden, 2015; Slattery, Sturt, Christianson, Yoshida, & Ferreira, 2013; Sturt, 2007). For example, non-canonical sentences like passives are prone to misinterpretation especially when they describe implausible scenarios (e.g., *The dog was bitten by the man*). Listeners not infrequently interpret such sentences as their plausible counterparts (e.g., that the dog, and not the man, was doing the biting) even though the syntax is unambiguous (Christianson et al., 2010; Ferreira, 2003). Similarly, garden-path sentences (e.g., *While the man hunted the deer ran into the woods*) can leave behind lingering incorrect interpretations in listeners (e.g., the deer as the Patient of the hunting action), particularly when those interpretations are plausible (e.g., compare the sentence above with: *While the man hunted the deer paced in the zoo*) (Christianson et al., 2001; Malyutina & den Ouden, 2015; Slattery et al., 2013; Sturt, 2007). These semantically conditioned interpretations can persist and compete with the correct interpretation even after the syntax is disambiguated (Sturt, 2007), or indeed even after the sentence appears to have been syntactically reanalyzed (Slattery et al., 2013).

Convergent evidence from electrophysiological (ERP) studies also indicates that semantic cues can lead to interpretations that compete with the one licensed by the syntax. For example, syntactically well-formed but semantically anomalous sentence fragments like “*The hearty meal was devouring...*” can elicit a P600 rather than an N400 signal despite unambiguous syntactic cues (Kim & Osterhout, 2005). This pattern is consistent with the parser relying on semantic information for thematic role assignment (*meal* as Patient of *devouring*), which triggers syntactic revision (to “*The hearty meal was devoured...*”) in order to satisfy the semantic fit (Kim & Osterhout, 2005; Kim & Sikos, 2011; see also Kuperberg, 2007; van Herten, Chwilla, & Kolk, 2006; cf. Chow & Phillips, 2013).

More broadly, several eye-tracking studies have shown that listeners integrate semantic information from the incoming input with prior or context-specific knowledge about events to rapidly assign and even anticipate thematic roles (see e.g., Kamide, Altmann, et al., 2003; Kamide, Scheepers, et al., 2003; Knoeferle et al., 2005). For example, in a study by Kamide and colleagues, listeners fixated on a motorcycle in the scene more than a carousel when they heard “*The man will ride...*”; and more on the carousel when they heard “*The girl will ride...*”, indicating that they integrated the meanings of the first noun and the verb

to anticipate upcoming referents (Kamide, Altmann, et al., 2003).

To summarize, sentence interpretation is guided not only by syntactic analysis of the input, but also by potentially independent semantic analysis (e.g., Christianson et al., 2010; Kim & Osterhout, 2005). While these sources of information frequently lead to the same interpretation, sometimes they point towards incompatible representations of sentence meaning. What cognitive mechanics allow listeners to resolve competition in such cases?

1.1. Cognitive control and resolving who did what to whom

Here, we test whether cognitive control engagement facilitates listeners’ ability to arrive at the correct thematic role assignment despite competing cues. For instance, upon hearing “*The fox was chas (phonetic transcription: /tʃeɪs/)*...”, listeners might initially consider both the Agent and Patient interpretations (fox as chaser and fox as flier). When later-arriving syntactic information (...*ed by the rabbit*) removes the temporary syntactic ambiguity and clearly indicates that the fox is the flier (the Patient), not the pursuer (the Agent), the parser might nevertheless continue to experience competition from the strong semantic cue because foxes typically chase rabbits, not vice versa. Resolution of such competition might rely on general cognitive control mechanisms that are used to detect and resolve information-conflict across domains, including recognition memory and language processing (Novick, Trueswell, & Thompson-Schill, 2005; see also Kaan & Swaab, 2002).

Convergent evidence from behavioral, neuroimaging, and neuropsychological studies broadly supports a link between cognitive control and language (Hsu & Novick, 2016; Hussey et al., 2017; Hussey, Ward, Christianson, & Kramer, 2015; January, Trueswell, & Thompson-Schill, 2009; Robinson, Shallice, & Cipolotti, 2005; Schnur et al., 2009; Snyder, Banich, & Munakata, 2011; Snyder, Banich, & Munakata, 2014; Thothathiri, Kim, Trueswell, & Thompson-Schill, 2012; Vuong & Martin, 2011, 2014, 2015; Ye & Zhou, 2009; inter alia). For example, overlapping brain regions in the left ventrolateral prefrontal cortex (hereafter left VLPFC) are activated within subjects by both canonical cognitive control tasks (Stroop, Flanker) and language processing tasks with competition between incompatible sentence interpretations (e.g., Hsu, Jaeggi, & Novick, 2017; January et al., 2009; van de Meerendonk, Rueschemeyer, & Kolk, 2013; Ye & Zhou, 2009). Damage to the same regions results in language deficits that are best characterized as an impairment in resolving competition at multiple levels of representation (e.g., Novick, Kan, Trueswell, & Thompson-Schill, 2009; Robinson et al., 2005; Schnur et al., 2009; Vuong & Martin, 2011). On the flip side, behavioral training that targets VLPFC-supported cognitive control functions, and non-invasive stimulation of this brain region yield improvements in the ability to correctly re-interpret garden-path sentences, suggesting a cause-and-effect interplay between cognitive control and syntactic ambiguity resolution (e.g., Hussey et al., 2015, 2017; Novick, Hussey, Teubner-Rhodes, Harbison, & Bunting, 2014). With respect to conflict between semantic and syntactic cues in particular, previous neuroimaging studies have shown that the left VLPFC, which is implicated in cognitive control, is activated more during the comprehension of sentences containing syntax-semantics conflict like the fox example above, compared to sentences without such conflict (Thothathiri et al., 2012; Ye & Zhou, 2009). This provides tantalizing *correlational* evidence by way of suggesting that the regions involved in cognitive control might also be involved in resolving conflict between thematic role assignments. However, it remains unknown if cognitive control processes engaged by a non-sentential task can *cause* listeners to suppress semantically attractive but erroneous thematic relations and choose a less plausible but correct interpretation during sentence comprehension.

We addressed this issue by relying on a phenomenon known as “conflict adaptation”—where conflict detection triggers sustained cognitive control, which facilitates the resolution of subsequent conflict

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