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Dynamic Engagement of Cognitive Control Modulates Recovery From Misinterpretation During Real-Time Language Processing

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Abstract

Speech unfolds swiftly, yet listeners keep pace by rapidly assigning meaning to what they hear. Sometimes, though, initial interpretations turn out to be wrong. How do listeners revise misinterpretations of language input moment by moment to avoid comprehension errors? Cognitive control may play a role by detecting when processing has gone awry and then initiating behavioral adjustments accordingly. However, no research to date has investigated a cause-and-effect interplay between cognitive-control engagement and the overriding of erroneous interpretations in real time. Using a novel cross-task paradigm, we showed that Stroop-conflict detection, which mobilizes cognitive-control procedures, subsequently facilitates listeners' incremental processing of temporarily ambiguous spoken instructions that induce brief misinterpretation. When instructions followed incongruent Stroop items, compared with congruent Stroop items, listeners' eye movements to objects in a scene reflected more transient consideration of the false interpretation and earlier recovery of the correct one. Comprehension errors also decreased. Cognitive-control engagement therefore accelerates sentence-reinterpretation processes, even as linguistic input is still unfolding.

Keywords

cognitive processes, comprehension, psycholinguistics, eye movements, monitoring, open data, open materials

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That people occasionally misunderstand what a speaker says is not newsworthy. Yet comprehension errors are usually fleeting—how do listeners revise instantly before communication hits an impasse and fails? Although people interpret language input moment by moment despite the hurtling rate of speech (Allopenna, Magnuson, & Tanenhaus, 1998; Altmann & Kamide, 1999), sometimes early interpretations, however efficient, must be revised when disconfirming evidence arrives promptly. Consider the following example:

1. Put the dumpling on the plate into the wok.

The phrase "on the plate" could specify either the dumpling's goal or information about one dumpling that distinguishes it from another (e.g., one on a platter). Listeners commit rapidly to the goal analysis, particularly when no other dumpling is mentioned, because the verb "put" requires a goal (Spivey, Tanenhaus, Eberhard, & Sedivy, 2002). Yet "into the wok" eventually signals the true goal of "put," which compels listeners to quickly revise their default characterization of "on the plate" as the dumpling's end point. What cognitive mechanics underlie listeners' ability to revise misinterpretations as input unfolds, allowing them to avoid comprehension fiascos?

One proposal claims that domain-general cognitive-control procedures, which detect and resolve conflict during information processing through flexible behavioral adjustments (Botvinick, Braver, Barch, Carter, & Cohen, 2001), also enable revision following linguistic

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misanalysis (Novick, Trueswell, & Thompson-Schill, 2005). Correlational patterns support this view: Patients with prefrontal damage and cognitive-control deficits fail to correct misinterpretations. For instance, when these patients listen to instructions such as Sentence 1 while viewing a scene containing the various elements mentioned in the sentence, they might put the dumpling on the plate, not in the wok, after their eyes lock on the false goal (i.e., the plate) in the visual scene (Novick, Kan, Trueswell, & Thompson-Schill, 2009; Vuong & Martin, 2011). Young children similarly fail (Trueswell, Sekerina, Hill, & Logrip, 1999) for reasons related to protracted cognitive-control development (Mazuka, Jincho, & Oishi, 2009; Nilsen & Graham, 2009). And neuroimaging data reveal overlapping brain activity when healthy adults interpret spoken ambiguities and complete nonsyntactic cognitive-control tasks, such as the Stroop task; such overlapping implies shared resources (Fedorenko, 2014; January, Trueswell, & Thompson-Schill, 2009; Ye & Zhou, 2009). These associative findings suggest that general-purpose cognitive-control functions may help listeners revise impulsive interpretations of sentence meaning. But is cognitive-control engagement what causes real-time revision to be fairly trouble free?

We investigated whether relative cognitive-control engagement facilitates revision. Our approach hinged on a key phenomenon of human cognition: that conflict detection initiates sustained cognitive control, which attenuates the cost of processing subsequent conflict (Gratton, Coles, & Donchin, 1992; Ullsperger, Bylsma, & Botvinick, 2005). For example, conflict experienced during the Stroop task (e.g., the word "yellow" printed in blue ink) diminishes if preceded by another conflict trial as opposed to a nonconflict trial (e.g., the word "blue" printed in blue ink; Freitas, Bahar, Yang, & Banai, 2007; Kerns et al., 2004). This behavioral savings reflects on-the-fly adjustments—*conflict adaptation*. Can such dynamic mobilization of cognitive control similarly redirect listeners' incorrect language-processing commitments? Using a novel cross-task-adaptation paradigm, we interleaved Stroop trials with a language-comprehension task involving syntactic ambiguity to test whether nonsyntactic-conflict detection initiates domain-general cognitive-control processes that facilitate real-time recovery from misinterpretation. We recorded eye movements as listeners executed spoken instructions: Because language input directs attention to relevant objects in the environment, fixation patterns provide important time-course information about listeners' ongoing interpretive commitments (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). This procedure allowed us to examine whether listeners' moment-to-moment interpretations depend on the relative engagement status of cognitive control, as determined by the prior Stroop trial type.

Method

Participants

Twenty-three right-handed people (7 men, 16 women; mean age = 20.4 years, range = 18–28 years) were paid $10 per hour for participating. They were healthy, native monolingual speakers of American English with normal or corrected-to-normal vision. All provided informed consent, and the human subjects review board at the University of Maryland approved all procedures. We excluded data from 3 participants because their eye-tracking calibration was poor (more than 33% of their data were lost). For the 20 remaining participants (see Chambers, Tanenhaus, & Magnuson, 2004, and Trueswell et al., 1999, for similar sample sizes), we excluded trials with more than 33% loss in eye-tracking data (5.3% of the data set).

Procedure and design

To test whether cognitive-control engagement facilitates recovery from misinterpretation, we pseudorandomly interleaved a Stroop task with a language-comprehension task involving syntactic ambiguity. In the language-comprehension task, participants listened to a sentence directing them to perform an action while viewing a scene composed of objects mentioned in the sentence (see Fig. 1). The meaning of the sentence they heard was either temporarily ambiguous or unambiguous, and the scene contained a target referent, a nontarget competitor referent, the correct goal, and the incorrect goal. Participants' task was to drag and drop the target onto the correct goal. Each critical trial was preceded by a Stroop task, in which ink colors and color names were congruent or incongruent.

All stimuli were presented using Experiment Builder software (Version 1.10.1241; SR Research, Kanata, Ontario, Canada). Eye movements were monitored with an EyeLink 1000 eye tracker (SR Research; temporal resolution: 1000 Hz; spatial resolution: ≤ 1.5°).

Stroop task. In the Stroop task, participants used a three-button mouse to indicate the ink color in which color names were printed on a computer screen. The response set always consisted of blue, green, and yellow. Color names matched ink colors on 60 congruent trials ("blue," "green," and "yellow" in blue, green, and yellow ink, respectively) but mismatched on 60 incongruent trials. We used only response-ineligible color names in the incongruent condition, that is, the color name did not match any color in the response set ("brown," "orange," and "red" in blue, green, or yellow ink). These trial types created conflict between representations, not conflict between responses (Milham et al., 2001). This manipulation ensured that the control mechanisms that engaged would be the

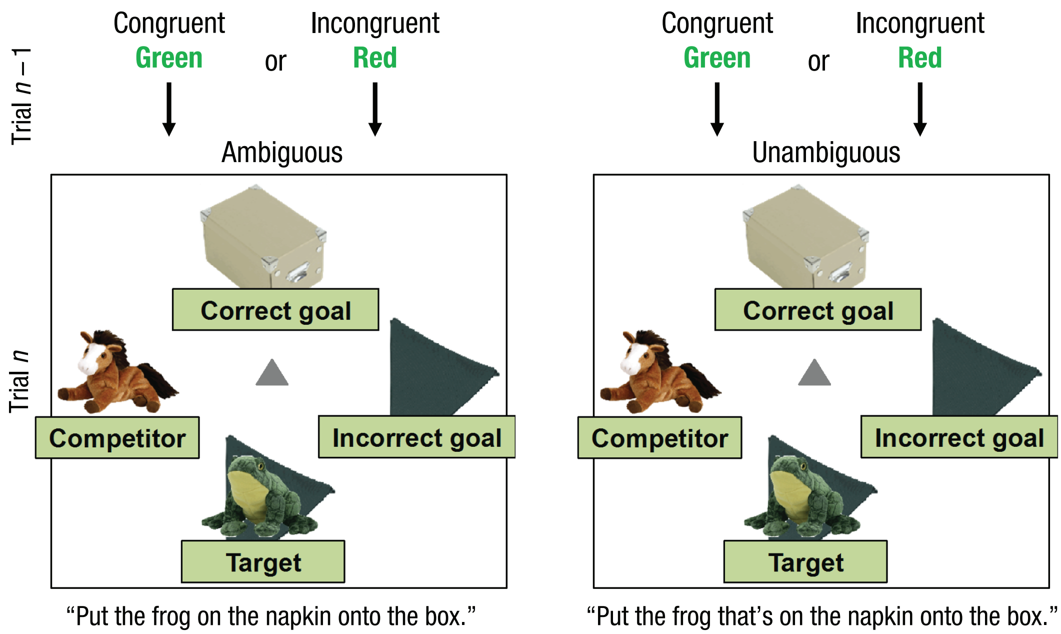

Fig. 1. Experimental design. Participants completed a series of ambiguous (left) and unambiguous (right) language-comprehension trials, each of which was preceded by a Stroop task. In the Stroop task, participants had to indicate the ink color of stimulus words, which was either congruent or incongruent with the word name. In the language-comprehension task, participants listened to a sentence directing them to perform an action. The sentence was either temporarily ambiguous (it was initially unclear whether the first prepositional phrase in the sentence provided a goal location or more information about the referent) or unambiguous (the insertion of the word "that's" clarified the sentence's meaning). While they heard the sentence, participants viewed a scene that contained objects mentioned in the sentence: a target, a competitor to the target, a correct goal, and an incorrect goal. Their task was to drag and drop the target item onto the correct goal.

same as those needed for the language task, in which conflict also arose from two different representations (i.e., interpretations). Response-based conflict may be handled by other control mechanisms (see Egner, 2007, 2008).

On each Stroop trial, the mouse cursor appeared at the center of the screen for 500 ms to serve as a fixation point. The cursor then disappeared and was replaced with the stimulus item, which remained on screen for 1,000 ms or until the participant responded, whichever came first.

Language-comprehension task. In the language-comprehension task, participants listened to and carried out spoken instructions, prerecorded by a female speaker, to drag and drop objects around a visual scene on a computer display. Instructions were given in single sentences, such as the following:

2. Put the frog on the napkin onto the box. (temporarily ambiguous)
3. Put the frog that's on the napkin onto the box. (unambiguous)

The visual scenes for these two examples contained a frog on a napkin (target), an empty napkin (incorrect goal), a box (correct goal), and a horse (competitor). Scenes therefore corresponded to contexts favoring the goal analysis, not the modifier analysis, of "on the napkin." In Sentence 2, "on the napkin," as in "on the plate" in Sentence 1, created temporary ambiguity between a goal interpretation (where to put the frog) and a modifier interpretation (the frog to be moved was currently on a napkin).

As ambiguous sentences such as Sentences 1 and 2 unfold, listeners tend to fixate on the incorrect goal location (an empty napkin in this case), which reveals early consideration of the goal analysis of the first prepositional phrase ("on the napkin"). However, late-arriving disambiguating evidence, such as "onto the box," signals the true destination (a box in this case), which forces listeners to revise their initial interpretation. With these kinds of sentences, eye movements to the correct goal (a box in this scene; see Fig. 1) are typically delayed, compared with eye movements to the correct goal when instructions are unambiguous (as in Sentence 3); this suggests that when sentences are ambiguous, extra time is needed to disengage from the incorrect goal analysis (Novick, Thompson-Schill, & Trueswell, 2008). In Sentence 3, "that's" removes the temporary ambiguity, imposing the modifier interpretation.

Participants heard 24 ambiguous, 24 unambiguous, and 48 filler sentences that all contained imperative "put" instructions. To minimize the salience of our manipulation and prevent participants from learning that postnominal prepositional phrases (e.g., "on the napkin") are always reduced-relative modifiers, we designed filler trials in which scenes visually resembled those in ambiguous or unambiguous trials (as in Fig. 1), but the instructions for which contained a postnominal locative prepositional phrase (e.g., "Put the cow on the sweater," in which "the sweater" is the correct destination). We expected this design feature to stop participants from adapting to reduced-relative constructions (Fine, Jaeger, Farmer, & Qian, 2013) and, therefore, avoiding the first empty object mentioned in a sentence (e.g., "napkin" in Sentences 2 and 3) as a possible response, because that strategy would be wrong half the time. Also, because filler sentences followed Stroop items in the same way that experimental sentences did, there were no contingent or predictive relationships between the prior Stroop type and the current sentence type, namely whether "the napkin" would be the correct or incorrect goal (Schmidt & De Houwer, 2011).

Participants used one mouse button to drag and drop relevant objects around the scene. We counterbalanced item locations (e.g., target, competitor, incorrect goal, correct goal) within and across conditions. We created two lists in which sentence ambiguity was counterbalanced within items: If an item was ambiguous in one list, it was unambiguous in its counterpart list (accomplished by inserting "that's"). Participants were randomly assigned to each list; we stopped data collection once participant numbers were balanced across lists. Just as in Stroop trials, language-comprehension trials began with the mouse cursor at the center of the screen for 500 ms to serve as a fixation point (so participants could not predict the upcoming task type). All objects in the display then simultaneously appeared around the cursor, and after a 300-ms delay, participants heard the instruction. They could move the mouse to execute an action as soon as the objects appeared. A digital camcorder filmed the computer screen to capture participants' drag-and-drop actions.

Interleaved Stroop-to-sentence sequences. At the start of the experiment, we presented participants with 20 color patches so that they could learn the mapping of mouse button to color response, which we counterbalanced across participants. Then, participants practiced a block of 144 Stroop trials (congruent and incongruent intermixed in equal proportion) before completing the pseudorandomly interleaved Stroop-sentence sequences. To test for cross-task conflict adaptation—namely, whether Stroop-conflict detection mobilizes cognitive-control procedures that expedite listeners' subsequent ability to recover from misinterpretation—we pseudorandomly interleaved Stroop trial types and language-comprehension trial types. We created 12 instances each of four conditions of interest: congruent Stroop trials with ambiguous language-comprehension trials (congruent-ambiguous pairings), incongruent Stroop trials with ambiguous language-comprehension trials (incongruent-ambiguous pairings), congruent Stroop trials with unambiguous language-comprehension trials (congruent-unambiguous pairings), and incongruent Stroop trials with unambiguous language-comprehension trials (incongruent-unambiguous pairings). That is, congruent or incongruent Stroop items (trial $n - 1$) could precede either ambiguous or unambiguous sentences (trial n). This design allowed us to determine the engagement status of cognitive control during spoken-language comprehension. Beyond these pairings, the inclusion of 48 filler sentences and 72 other Stroop trials created several sentence-to-Stroop pairings, sentence-to-sentence pairings, Stroop-to-Stroop pairings, and Stroop-to-sentence pairings, which prevented participants from predicting upcoming trial or task type and from learning contingent relationships between tasks (prior and current trial type). Given our focus on how cognitive-control engagement affects language comprehension per se, our analyses and discussion focus primarily on listeners' real-time processing of the instructions as the outcome measure.

Analysis

On Stroop trials, we collected accuracy and response time data. On language-comprehension trials, we collected mouse-action and eye-movement data. Participants performed a correct action if they dragged the target directly to the correct goal (e.g., box); they performed an incorrect action if they dragged the target to the incorrect goal (e.g., empty napkin; see Trueswell et al., 1999). For eye movements, each quadrant of the screen was labeled as an interest area, and sample reports from the EyeLink Data Viewer tool (Version 2.2.62; SR Research) determined fixation proportions.

Unless otherwise stated, statistical analyses were performed using the lme4 software package (Bates, Mächler, Bolker, & Walker, 2015) in the R programming environment (R Development Core Team, 2014). We fit mixed-effects logistic regression models that included sentence type, Stroop trial type, and their interaction as fixed effects to predict (a) action responses, (b) the proportion of looks to the correct goal (indicating revision of an initial misinterpretation), and (c) looks to the incorrect goal (indicating consideration of the wrong interpretation). We crossed participants and items as simultaneous random effects on the intercept, and we note when the inclusion of random slopes improved overall model fit (see Huang, Zheng, Meng, & Snedeker, 2013).[1] The critical contrast was between incongruent-ambiguous and congruent-ambiguous pairings, to test whether Stroop-conflict detection, and thus cognitive-control engagement, facilitates recovery from misinterpretation of temporarily ambiguous phrases.

Results

Our results are organized to address three questions: When cognitive control is more activated, do listeners (a) commit fewer off-line action errors (involving the incorrect goal); (b) have an easier time revising their interpretations of sentences, reflected in earlier looks to the correct goal (e.g., box); and (c) consider the incorrect goal (e.g., empty napkin) to a lesser extent?

Action responses

Figure 2a shows that participants committed more action errors in the ambiguous condition (M = .137, 95% confidence interval, or CI = [.080, .195]) than in the unambiguous condition (M = .022, 95% CI = [.005, .041]), $\chi^2(1, N = 20) = 4.29$, p = .038 (slopes included in the model). Figure 2b shows that prior Stroop trial type, and thus relative cognitive-control engagement, modulated the ambiguity effect but had no impact under unambiguous conditions. This was confirmed by a significant sentence-type-by-Stroop-trial-type interaction, $\chi^2(1, N = 20) = 6.34$, p = .012 (slopes included in the model): Specifically, participants reliably made fewer errors on ambiguous trials when they were preceded by incongruent Stroop trials (M = .079, 95% CI = [.030, .129]) than by congruent Stroop trials (M = .196, 95% CI = [.119, .273]), $\chi^2(1, N = 20) = 6.63$, p = .010, but on unambiguous trials, the preceding Stroop trial type made no significant difference. This result suggests that cognitive-control engagement helps prevent comprehension errors.

Looks to the correct goal

Does cognitive-control engagement facilitate real-time revision? Dwell times on the correct goal revealed the expected ambiguity effect: Listeners fixated on the correct goal less during ambiguous trials (M = .328, 95% CI = [.303, .353]) than during unambiguous trials (M = .374, 95% CI = [.358, .390]), $\chi^2(1, N = 20) = 16.33$, p < .001. Figure 3 plots the proportion of looks to the correct goal from the onset of the first prepositional phrase (e.g., "on the napkin") through the end of the sentence, separately for each previous Stroop trial type. As can be seen, on ambiguous trials, participants looked more to the correct goal when the prior Stroop trial was incongruent than when it was congruent. The proportion of looks to the correct goal on unambiguous trials were unaffected by prior Stroop trial type. A significant sentence-type-by-Stroop-trial-type interaction confirmed this observation, $\chi^2(1, N = 20) = 6.14$, p = .013: Cognitive-control engagement modulated consideration of the correct goal under ambiguous (but not unambiguous) conditions (congruent-ambiguous pairings: M = .305, 95% CI = [.279, .331]; incongruent-ambiguous pairings: M = .353, 95% CI = [.325, .381]; p < .001). This interaction remained significant when including only correct-action trials, $\chi^2(1, N = 20) = 4.38$, p = .036.

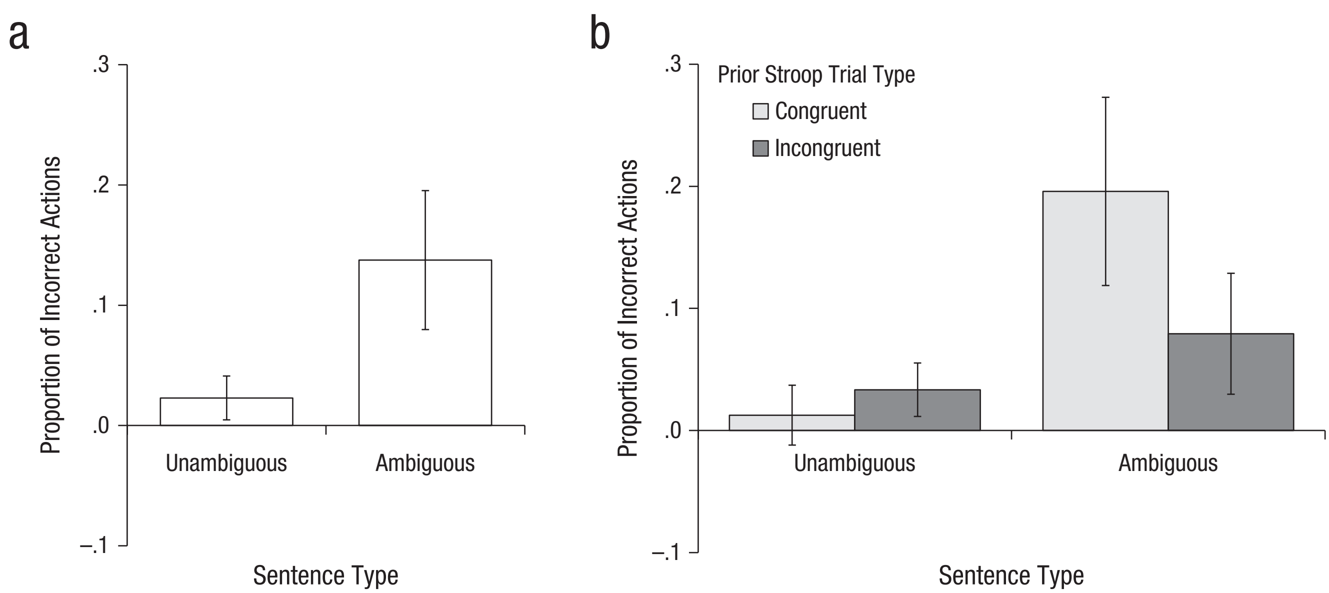

Fig. 2. Mean proportion of action errors. Results are shown separately (a) for each sentence type overall and (b) for each sentence type as a function of the prior Stroop trial type. Error bars indicate 95% confidence intervals.

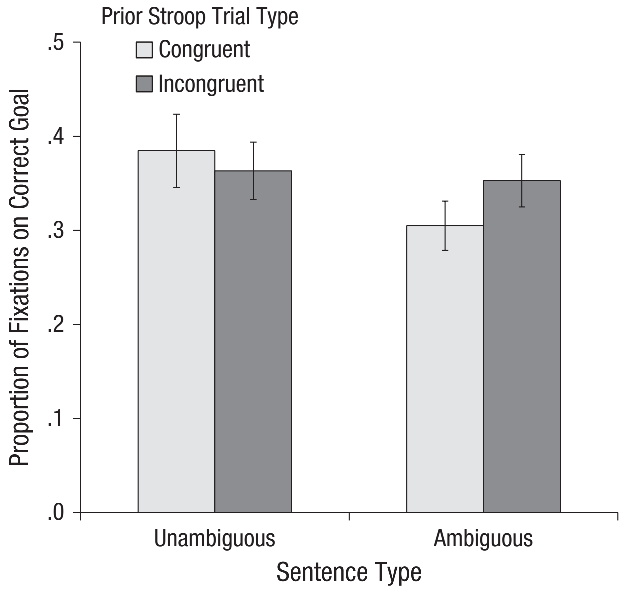

Fig. 3. Mean proportion of fixations on the correct goal (e.g., "box") as a function of sentence type and prior Stroop trial type. Fixations were measured from the onset of the first prepositional phrase (i.e., the onset of the temporary ambiguity in the ambiguous condition) through the end of the sentence. Error bars indicate 95% confidence intervals.

Figure 4a plots the proportion of fixations on the correct goal over each region of the unfolding sentence. At the onset of the correct-goal phrase (i.e., the arrival of disambiguating evidence; e.g., "onto . . ." in Sentences 2 and 3), participants fixated on the correct goal less during ambiguous trials than during unambiguous trials. However, they appeared to recover earlier when incongruent Stroop trials, as opposed to congruent Stroop trials, preceded the ambiguity. Figure 4b zooms in on this time course, indeed showing that between 200 and 600 ms following the onset of the correct-goal word (e.g., "box"),[2] listeners considered the correct goal earlier when cognitive control was relatively engaged (i.e., on incongruent Stroop trials compared with congruent Stroop trials). This was confirmed by a significant sentence-type-by-Stroop-trial-type interaction: Looks to the correct goal were greater during incongruent-ambiguous pairings (M = .711, 95% CI = [.647, .775]) than during congruent-ambiguous pairings (M = .639, 95% CI = [.571, .707]), $\chi^2(1, N = 20) = 6.57$, $p = .010$, but not during incongruent-unambiguous trials as compared with congruent-unambiguous trials. A similar pattern emerged when examining only correct-action trials, $\chi^2(1, N = 20) = 3.39$, $p = .065$. Interestingly, as can be seen in Figure 4b, looking patterns in this 400-ms window for incongruent-ambiguous pairings paralleled those for unambiguous sentences—congruent-unambiguous vs. incongruent-ambiguous pairings: $\chi^2(1, N = 20) = 1.93$, $p = .165$; incongruent-unambiguous vs. incongruent-ambiguous pairings: $\chi^2(1, N = 20) = 1.40$, $p = .236$. This finding indicates that cognitive-control engagement reliably accelerates recovery from misinterpretation.

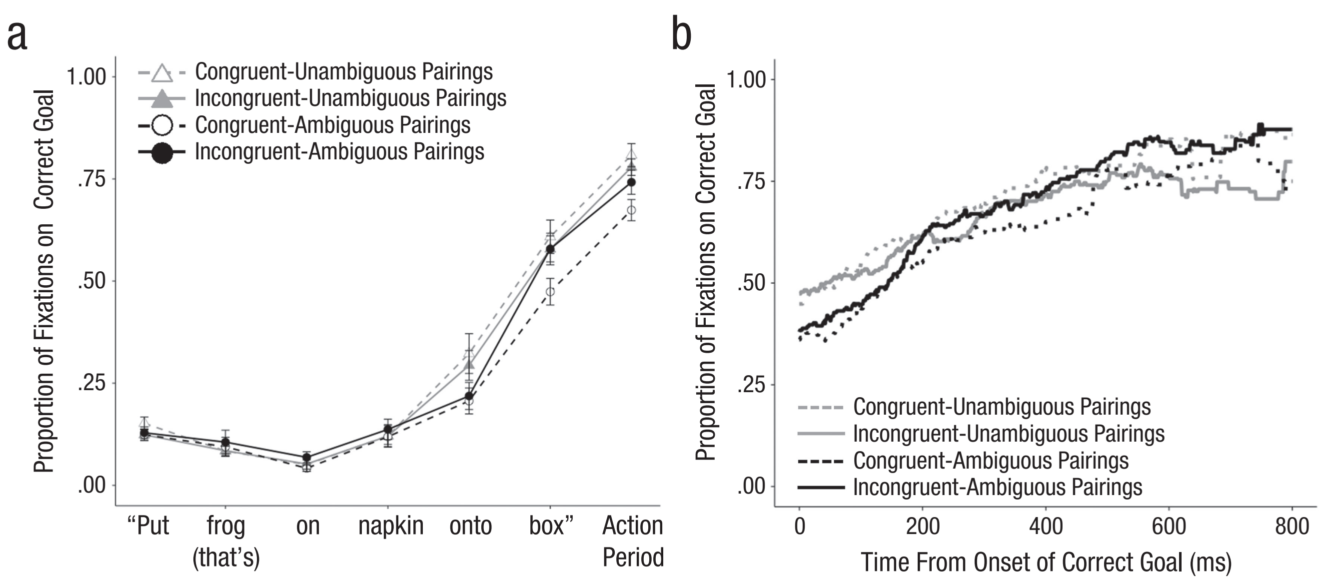

Fig. 4. Mean proportion of fixations on the correct goal over time for each of the four pairings of Stroop trial type and sentence type. Results are shown separately (a) across the sentence regions of the language-comprehension trials and (b) for an 800-ms window starting with the onset of the correct-goal word ("box" in this example). Each word on the x-axis in (a) indicates the beginning of a new sentence region. The time span corresponding to each data point varied across sentences because some words took longer to utter than others. Error bars indicate 95% confidence intervals.

Looks to the incorrect goal

When cognitive control engages, do listeners consider the incorrect-goal interpretation less? Figure 5a plots the proportion of fixations on the incorrect goal from the onset of the incorrect-goal word (e.g., "napkin") until the onset of the correct-goal phrase (e.g., "onto"). The expected ambiguity effect can be clearly seen: Participants looked more to the incorrect goal under ambiguous conditions (M = .096, 95% CI = [.075, .117]) than under unambiguous conditions (M = .069, 95% CI = [.056, .082]), $\chi^2(1, N = 20) = 33.25$, $p < .001$. Figure 5b shows that the preceding Stroop trial type modulated the effect: Consideration of the incorrect goal decreased under ambiguous conditions if the prior Stroop trial was incongruent. This was confirmed by a significant sentence-type-by-Stroop-trial-type interaction: Relative cognitive-control engagement reduced looks to the incorrect goal in incongruent-ambiguous pairings (M = .076, 95% CI = [.055, .097]) relative to congruent-ambiguous pairings (M = .118, 95% CI = [.087, .149]), $\chi^2(1, N = 20) = 4.19$, $p = .041$; no reliable difference emerged between incongruent-unambiguous and congruent-unambiguous pairings. This finding suggests that cognitive-control engagement attenuates consideration of the wrong interpretation and facilitates disengagement from it.

Engagement of cognitive control

Do participants actually experience Stroop conflict and consequently engage cognitive control? The evidence thus far strongly indicates that relative cognitive-control engagement facilitates listeners' recovery from sentence misinterpretation in real time. Yet this interpretation assumes that cognitive control has been initially engaged during the Stroop task, which influences the subsequent language-comprehension task. Are the findings we have reported contingent on the experience of Stroop conflict in the first place? We ask this in the context of prior evidence demonstrating that Stroop effects can dissipate over time with practice (MacLeod, 1991).[3]

Indeed, when testing correct-goal fixations from the onset of the correct-goal word (e.g., "box"), we observed a marginally significant three-way interaction among experimental half (first vs. second), Stroop trial type, and sentence type, $\chi^2(1, N = 20) = 9.11$, $p = .058$, which suggests that our effects were moderated by time. Given the theoretical importance of evaluating the effectiveness of the Stroop manipulation, we therefore separated the data into halves to test the modulating effects of Stroop trial type on subsequent syntactic-ambiguity resolution. Paired-sample t tests revealed that participants were slower to respond to incongruent than to congruent

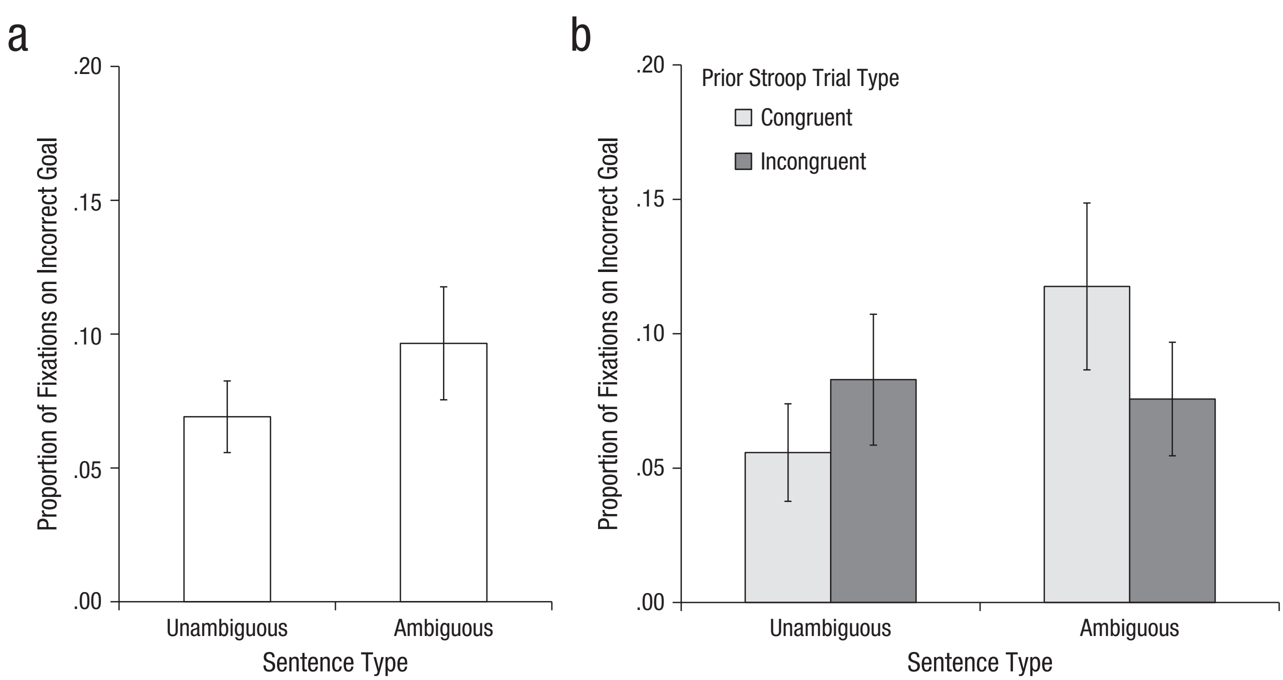

Fig. 5. Mean proportion of fixations on the incorrect goal from the onset of the incorrect-goal word (e.g., "napkin") to the onset of the correct-goal phrase (e.g., "onto"). Results are shown separately (a) for each sentence type overall and (b) for each sentence type as a function of the prior Stroop trial type. Error bars indicate 95% confidence intervals.

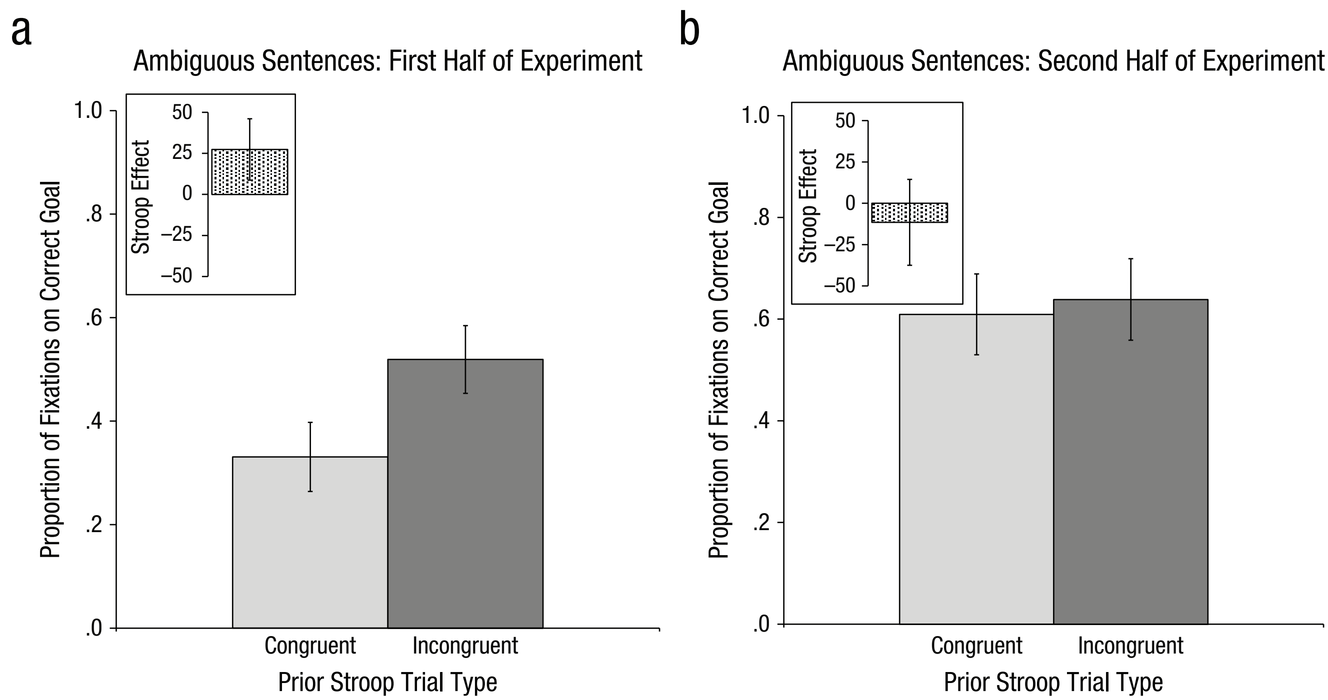

Fig. 6. Mean proportion of fixations on the correct goal in the ambiguous condition as a function of prior Stroop trial type, separately for the (a) first half and (b) second half of the experiment. The insets show the Stroop effect, that is, the difference between mean response time on incongruent minus congruent Stroop trials. Error bars indicate 95% confidence intervals.

Stroop trials during the first half (60 trials) of the experiment—incongruent minus congruent: M = 27 ms, 95% CI = [8, 46], $t(19) = 2.86$, $p = .010$—but not the second half of the experiment—incongruent minus congruent: $M = -11$ ms, 95% CI = [–37, 15], $t(19) = -0.87$, $p > .250$. Consequently, if conflict-control procedures per se are involved in shaping the revision of language interpretations, as we have argued, then the findings reported above (e.g., looks to the correct goal) should be observed in only the first half of the experiment (six incongruent-ambiguous vs. congruent-ambiguous pairings).

Importantly, as Figure 6 shows, planned contrasts revealed that in the first half of the experiment, when there was a significant Stroop effect, looks to the correct goal under ambiguous conditions were modulated by prior conflict detection (congruent-ambiguous pairings: M = .331, 95% CI = [.264, .398]); incongruent-ambiguous pairings: M = .519, 95% CI = [.454, .584]), $\chi^2(1, N = 20) = 5.52$, $p = .019$. In the second half of the experiment only, in the absence of a Stroop effect, this modulation disappeared (congruent-ambiguous pairings: M = .609, 95% CI = [.525, .693]; incongruent-ambiguous pairings: M = .639, 95% CI = [.559, .719]), $\chi^2(1, N = 20) = 1.66$, $p = .197$. Together, this evidence suggests that conflict detection per se, and the theoretical engagement of cognitive control, is actually influencing language-reinterpretation processes.

Discussion

How do listeners effortlessly override misinterpretations of linguistic input? Our findings reveal a cause-and-effect interplay between cognitive-control engagement and revising erroneous processing commitments. When nonsyntactic cognitive-control resources mobilized following Stroop-conflict detection, listeners committed fewer comprehension errors, considered the correct interpretation more, and dwelled on the incorrect interpretation less, compared with relative cognitive-control unengagement. Moreover, revision was immediate: 200 ms after the onset of the correct-goal word (e.g., "box"), eye movements to the correct goal were indistinguishable from those during unambiguous instructions. This uncovered a 400-ms revision advantage compared with relative cognitive-control inactivity, which suggests that adjusting misinterpretations moment to moment draws dynamically on general-purpose cognitive-control procedures as linguistic input rapidly unfurls.

Ample evidence suggests that the language-processing system readily accesses multiple linguistic and extralinguistic cues to interpretation that guide listeners' resolution of syntactic ambiguity (Altmann & Steedman, 1988; Chambers et al., 2004; Garnsey, Pearlmutter, Myers, & Lotocky, 1997). For example, a scene with two frogs, one on a napkin and one not, helps listeners revise because it supports the modifier interpretation of "on the napkin" by providing distinguishing information about the intended frog (Novick et al., 2008; Spivey et al., 2002). While listeners can avoid ambiguity pitfalls by consulting multiple evidential sources, our findings discern aspects of a mental architecture that enables the system to monitor the coordination of these sources, which may conflict at any moment: Active cognitive control can mitigate conflicting cues to interpretation.

Two prior studies suggest a cause-and-effect interplay between cognitive control and language: Training cognitive control predicts better sentence reinterpretation over time (Novick, Hussey, Teubner-Rhodes, Harbison, & Bunting, 2014), and readers' discovery of a language misinterpretation attenuates subsequent Stroop-conflict effects (Kan et al., 2013). Thus, comprehension difficulty recruits cognitive control. Our research uniquely shows that dynamic recruitment of conflict-control procedures affects real-time recovery from misinterpretation.

Could these effects be ascribed to greater vigilance rather than to conflict-control procedures? Perhaps participants become more watchful after "tricky" Stroop-incongruent trials. This account also predicts that listeners look less at the incorrect goal when hearing the incorrect-goal phrase (e.g., "on the napkin") because they are ready for trickery and quickly recognize the phrase as a reduced-relative modifier. However, filler sentences should have strongly prevented participants from anticipating reduced relatives; thus, mere vigilance following Stroop conflict would be an imperfect strategy (see also Kan et al., 2013).

Our filler design also safeguarded against participants implicitly tracking contingencies between Stroop and sentence tasks, because prior Stroop trial type did not predict whether the first prepositional phrase they heard (e.g., "on the napkin") would be the correct or incorrect goal. Even if such cross-task contingencies existed, a learning account would predict increased, not decreased, cross-task effects over time, as participants noticed any contingencies. Clearly, our data do not fit this pattern.

We conclude then that cognitive control may act when even minor language-comprehension adjustments are necessary to avoid total failure. During processing, multiple interpretations at various levels (words, sentences) are rapidly activated and deactivated, even if these alternatives do not reach conscious awareness (Dahan & Gaskell, 2007; McRae, Spivey-Knowlton, & Tanenhaus, 1998). Dynamic engagement of cognitive control may conspire with linguistic and extralinguistic constraints to reduce activation of irrelevant alternatives, enabling listeners to override language misinterpretations within milliseconds.

Author Contributions

N. S. Hsu and J. M. Novick contributed equally to the study concept, experimental design, data analysis and interpretation, and writing and revising of the manuscript. N. S. Hsu collected the data. Both authors approved the final version of the manuscript for submission.

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Open Practices

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Notes

1. For each analysis, we selected the final model by including all fixed effects (i.e., the main effects and their interaction) then removing predictors until the reduced model did not perform significantly better than the full model ($p > .05$). We also constructed each model with random slopes on the interaction, but random slopes were typically excluded from further analyses because their inclusion did not improve overall fit.

2. We derived this window by first calculating the proportion of time spent looking at the correct goal from the onset of hearing the correct-goal word on a millisecond-by-millisecond basis. We shifted the window 200 ms after the onset of the correct-goal word to account for the time that it takes to launch an eye movement after it has been planned, because any eye movements earlier than this to the correct goal could not theoretically be due to hearing the word indicating that

goal (because that is not enough time to make a saccade). We analyzed a coarse-grain window from 200 ms until the offset of the sentence (i.e., the onset of the action period when participants began to make a mouse movement), with the sentence-type-by-Stroop-trial-type interaction emerging in the first 400 ms, as assessed by binning eye movements into 50-ms increments.

3. Alternative analyses could address whether the experience of conflict modulates behavioral adjustments. For example, Kan et al. (2013) took an individual-differences approach to demonstrate that the more perceptual ambiguity one experiences, the smaller the subsequent Stroop-conflict effect. We likewise considered testing whether individual differences in Stroop performance predicted listeners' subsequent syntactic-ambiguity resolution. However, in a separate experiment, Kan et al. interleaved a reading task with the Stroop task (their outcome measure). While the Stroop effect was attenuated more often following ambiguous than unambiguous sentences, an individual's sentence-ambiguity effect did not predict his or her subsequent Stroop-conflict effect. We therefore reasoned that a time-based analysis might be more informative than an individual-differences analysis for our causal questions.

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