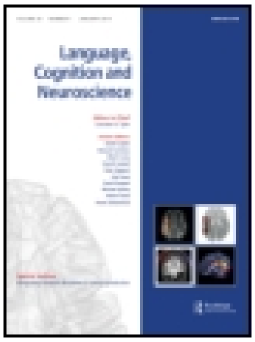

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REGULAR ARTICLE

Direct impact of cognitive control on sentence processing and comprehension

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ABSTRACT
Incremental language processing means that listeners confront temporary ambiguity about how to structure the input, which can generate misinterpretations. In four "visual-world" experiments, we tested whether engaging cognitive control – which detects and resolves conflict – assists revision during comprehension. We recorded listeners' eye-movements and actions while following instructions that were ripe for misanalysis. In Experiments 1 and 3, sentences followed trials from a nonverbal conflict task that manipulated cognitive-control engagement, to test its impact on the ability to revise. To isolate conflict-driven effects of cognitive-control on comprehension, we manipulated attention in a non-conflict task in Experiments 2 and 4. We observed fewer comprehension errors, and earlier revision, when cognitive control (more than attention) was elicited on an immediately preceding trial. These results extend previous correlations between cognitive control and language processing by revealing the influence of domain-general cognitive-control engagement on the temporal unfolding of error-revision processes during language comprehension.

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Introduction

Understanding spoken language requires listeners to quickly extract meaning from a fast-unfolding utterance. Despite the continuous rush of sounds, listeners are strikingly adept at processing the input on the fly – categorising phonemes (Holt & Lotto, 2010), recognising words (Allopenna et al., 1998; Marslen-Wilson, 1987), and interpreting phrases and sentences with only partial acoustic input (Altmann & Kamide, 1999) – using information from both the linguistic signal and the contextual environment to guide comprehension moment by moment (Spivey et al., 2002). Yet incremental interpretation, however efficient, means that listeners must deal with temporary ambiguity that occurs at multiple levels of representation. This can create potential pitfalls to successful communication. For instance, listeners' initial interpretations of sentence meaning sometimes turn out to be wrong, when evidence that arrives late in an utterance conflicts with earlier cues, forcing the need to revise. Consider 1:

1. Put the horse on the binder onto the scarf.

While following such instructions, eye-gaze studies show that as listeners hear "on the binder", they look at an empty binder in the scene (see Figure 1), indicating that they were interpreting the phrase as a goal, namely, where the horse should go (Novick et al., 2008; Tanenhaus et al., 1995). Listeners' commitment to this analysis arises because the verb "Put" requires a location (a speaker cannot tell someone to put something without telling them *where*), and "on the binder" quickly satisfies this constraint. However, following the onset of "onto the scarf", listeners scan the scene and realise that "on the binder" was really a modifier that provided more information about the horse – that currently, it's on a binder. They then correct their initial misinterpretation of "on the binder" to allow the scarf to be the actual goal.

Unsurprisingly, adult listeners can adjust their interpretations in real time, rarely failing to understand what a speaker says. But the apparent ease with which we interpret spoken language betrays the intricate (albeit subtle) role that cognitive-control systems may play to help ensure that comprehension stays on track. In this paper, we are interested in how listeners regulate their interpretations of sentence meaning, particularly how they rapidly correct errors before comprehension runs aground. Under the cognitive-control model of syntactic revision, recovering from misinterpretation

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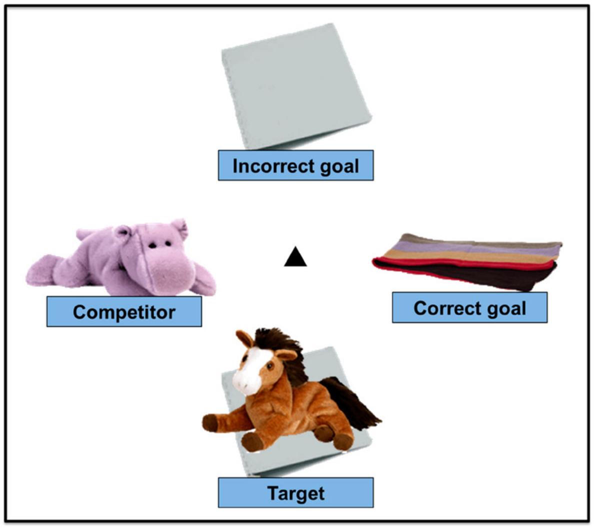

Figure 1. Visual scene that accompanies "Put the horse [that's] on the binder onto the scarf". Sample display features a target (horse on a binder), a competitor (hippo), an incorrect goal (empty binder), and correct goal (scarf).

involves cognitive control because of the need to resolve among *conflicting representations* of the input. Specifically, late-arriving linguistic evidence (e.g. "onto the scarf" in example 1) signals the true goal of "Put", which conflicts with listeners' early preference to interpret "on the binder" as the horse's destination. In this way, conflict-control processes are hypothesised to engage when the parsing system must override, in real time, a default way of interpreting an unfolding sentence in favour of a less preferred one (Novick et al., 2005).

This account thus makes the critical prediction that there is a causal interplay between the relative engagement status of cognitive control and effective recovery from misanalysis. Yet most of the evidence supporting this proposal is correlational and has not examined the immediate impact of cognitive control on revision procedures. In addition, prior work testing this account has not isolated control mechanisms from other types of cognitive engagement that may occur in challenging conditions as a factor in real-time syntactic revision. An unresolved matter then is whether online revision occurs through a process of conflict detection and the engagement of control, or more broadly because increases in task difficulty heighten demands on the top-down systems that support effortful speech perception and processing. Put another way, difficulty is not a mechanism itself: tasks may require considerable mental effort for variable reasons (e.g. calculus vs. parallel parking), and thus may be handled by different (albeit related) cognitive processes. Indeed, multiple neural networks support the control of attention and are thought to contribute to effortful speech understanding (Peelle, 2018). In general, these attention networks support our ability to maintain task goals across prolonged periods of time, allow us to orient to sensory input, collect information from the signal, and detect conflict across competing characterisations of the input, which are handled by separate attention-related networks (Petersen & Posner, 2012). Here, we test whether harder versions of a sentence-processing task, due to temporarily competing interpretations, are eased not just because listeners increasingly engage when confronted with a task requiring greater effort, but more specifically because cognitive control has been recruited to handle competitive interactions.

Our hypothesis is that cognitive control regulates thoughts and actions when the intended characterisation of the input conflicts with a more dominant one. For example, conflict-driven cognitive-control engagement will help listeners revise an interpretation of a sentence after discovery of a misanalysis, by biasing internal representations toward relevant over prepotent-but-irrelevant ones (Novick et al., 2005). While related to the control of attention more broadly, we view conflict-driven cognitive control as acting on *endogenous* representations, whereas attention regulates the collection of *exogenous* information from the environment. Specifically, the regulation of mental activity that follows conflict detection operates to adjust internal representations (e.g. how a stimulus is characterised). By contrast, we view attention control as a sustained, rather than a transient process, which involves maintaining focus over the duration of a trial or throughout a mental event that has some temporal extent. In general, attention control supports humans' ability to orient to sensory input and gather information from the signal across prolonged periods of time (see General Discussion).

Finally, prior data have been mainly limited to correlations between tasks that contain verbal material (e.g. letters, words, sentences). Consequently, questions remain about whether the cognitive-control mechanisms that support syntactic revision are domain-general, namely if they function systematically over a variety of representations regardless of whether the conflict derives from a verbal source.

In what follows, we review what we currently know about the role of cognitive control in sentence interpretation. The evidence demonstrates that revising misinterpretations recruits the same brain areas as separate cognitive-control tasks that do not involve syntactic material, and that populations with poor cognitive control have difficulty overriding early processing commitments. These correlational findings suggest that conflict-resolution abilities support sentence revision by employing a common neural system. However, whether cognitive-control procedures (rather than, say, maintaining attention over the duration of a trial) alters recovery from misanalysis is still unclear, as is the extent to which these procedures are domain-general.

Cognitive control and revising sentence misinterpretations: what we know

Representational conflict denotes cases in which current task demands require overriding a dominant (or "prepotent") way of characterising a stimulus, or when multiple response options compete for selection because none is more compelling than another (so-called "underdetermined conflict"). Conflict detection triggers the regulation of mental activity that serves to resolve among competing representations (Botvinick et al., 2001). Such cognitive-control engagement thus helps to guide goal-directed behaviour in accordance with task-specific requirements by biasing task-relevant over -irrelevant information (see also Desimone & Duncan, 1995; Miller & Cohen, 2001; Norman & Shallice, 1986).

Support for the cognitive control model of syntactic revision comes from neuroimaging and neuropsychological evidence showing that brain areas associated with syntactic revision are also associated with non-linguistic tasks designed to tap cognitive control, particularly the left inferior frontal gyrus (LIFG). Neuroimaging studies of sentence processing indicate that syntactically ambiguous sentences activate the LIFG (Mason et al., 2003). This same region is activated in studies of cognitive control under conditions of conflict in a range of tasks, including Stroop (Milham et al., 2001), Flanker (Ye & Zhou, 2009), and proactive interference in memory (Gray et al., 2003; Jonides & Nee, 2006). Particularly compelling evidence for a shared conflict-resolution mechanism comes from findings that canonical cognitive-control tasks (e.g. Stroop) and syntactic ambiguity resolution co-localize in the LIFG within individual brains (January et al., 2009; Hsu et al., 2017). Co-localization within the LIFG has also been observed for Stroop-conflict and a sentence comprehension task that was difficult to understand because of a visually degraded signal (i.e. the text was hard to see) (van de Meerendonk et al., 2013). One inference from such data is that a lack of bottom-up information can create perceptual ambiguity and thus competition among multiple underdetermined interpretations of a sentence. This in turn signals a demand for cognitive-control adjustments to resolve linguistic competition.

In convergent findings, patients with LIFG damage show deficits resolving conflict during Stroop and memory-interference tasks (Hamilton & Martin, 2005) and also fail to correct early misinterpretations of sentence meaning (Novick et al., 2009; Vuong & Martin, 2011). For example, like healthy adults, eye-movement patterns show that they incrementally commit first to the goal analysis of "on the binder" in (1). But unlike healthy adults, they cannot revise despite evidence from late-arriving cues like "onto the scarf". Offline hand-actions show that these patients typically move the horse to the incorrect goal (e.g. the empty binder in Figure 1) rather than the correct goal (e.g. the scarf) (Novick et al., 2009; Vuong & Martin, 2011). Five-year-old children show a similar pattern of revision failure (Trueswell et al., 1999; Weighall, 2008), which has been ascribed to the protracted maturation of cognitive-control abilities (Davidson et al., 2006; Zelazo & Frye, 1998; cf Huang & Hollister, 2019) that coincide with slow maturation of prefrontal cortex, including the LIFG (Mazuka et al., 2009; Novick et al., 2005).

Critically however, patients (and young children) have no trouble understanding *unambiguous* sentences like (2):

2. Put the horse that's on the binder onto the scarf.

Here, the complementizer "that's" imposes the modifier (and prevents the goal) analysis of "on the binder". Because patients interpret such sentences correctly – moving the horse that's currently on a binder directly to the scarf – it suggests that their difficulty under ambiguous conditions is related to revision demands and a failure to resolve among competing representations, rather than an absence of relevant syntactic representations. Indeed, even healthy adults fail to revise sometimes, suggesting that misinterpretations do not necessarily reflect a lack of knowledge (Hsu & Novick, 2016; Novick et al., 2008; see also Christianson, 2001; Ferreira, 2003; Gibson et al., 2013; Slattery et al., 2013).

Cognitive control and revising sentence misinterpretations: a causal link?

The findings summarised above suggest that cognitive control supports the ability to recover from misinterpretations of language input. However, one limitation of prior work is that correlational patterns of data (such as co-activated brain regions across different tasks, or co-impairments in patients) do not add to our understanding of how cognitive control may directly influence revision. Under the cognitive-control model of syntactic revision, late-arriving linguistic input that conflicts with listeners' initial interpretation should trigger conflict-control processes that facilitate recovery from misanalysis (Novick et al., 2005). Thus, inherent in this proposal is a cause-and-effect mechanism; but other methods are needed to address what underlies this connection. If cognitive control enables listeners to resolve conflict, its dynamic engagement should influence the ability to re-interpret sentence meaning in real time.

Some emerging data are consistent with a causal link. For example, in two studies, multi-week training on a memory task targeting conflict resolution (N-back with lures) led to posttest improvements on the trained task and also in sentence revision, indexed by both online (eye-tracking) and offline (comprehension accuracy) measures (Hussey et al., 2017; Novick et al., 2014). Moreover, multi-week training on an equally difficult memory task that did not involve conflict resolution (N-back with no lures) led to posttest benefits on the trained task, but it did not produce posttest benefits in sentence revision. This suggests that the effects of training on syntactic ambiguity resolution were specific to a conflict-resolution process that could not be ascribed simply to increased memory or attention during the intervention (Hussey et al., 2017). Similarly, 30 minutes of transcranial direct current stimulation (tDCS) over left prefrontal cortex during a task has been shown to improve sentence comprehension and N-back performance under conditions requiring cognitive control (Hussey et al., 2015). These findings show that experimentally modulating neural networks associated with cognitive control can have downstream causal effects on sentence revision abilities.

However, the training and neuromodulation research does not address whether cognitive-control functions took effect "in the moment" when performing the post-training language assessments. That is, one assumes that the cognitive-control intervention strengthened a mechanism that triggered as the posttest sentence comprehension task required revision (conflict resolution). But by taking place over several weeks, the pre/post training paradigm was not designed to uncover such processing dynamics.

Hsu and Novick (2016) developed a paradigm that tests how *dynamic modulations* of cognitive-control engagement over the course of seconds affects sentence revision. The method capitalises on a phenomenon known as "conflict adaptation". In adults, detecting conflict engages cognitive control, which biases processing away from irrelevant characterisations of a stimulus and thus facilitates resolution of ensuing conflict. For example, performance on an incongruent Stroop trial (e.g. YELLOW in blue ink) is faster and more accurate when it follows another incongruent trial (e.g. GREEN in red ink) compared to a congruent trial (e.g. GREEN in green ink; Egner & Hirsch, 2005; Freitas et al., 2007; Gratton et al., 1992; Kerns et al., 2004). Similar patterns emerge in other tasks eliciting representational and/or response conflict, e.g. Flanker (Duthoo et al., 2014; Ullsperger et al., 2005) and Simon (Hommel et al., 2004; Weissman, 2020). Using a novel cross-task paradigm, Hsu and Novick (2016) interleaved Stroop trials with a spoken comprehension task involving syntactic ambiguity to evaluate dynamic regulation of sentence interpretations through cross-task adjustments in cognitive control. When ambiguous sentences (e.g. those in example 1) followed incongruent Stroop items, compared with congruent Stroop items, adults' eye movements to objects in the visual world reflected greater consideration of the correct goal (e.g. the scarf in Figure 1). Moreover, offline errors involving the incorrect goal (e.g. the empty binder) decreased reliably. These patterns suggest that the mobilisation of cognitive-control mechanisms influences revision, namely that reinterpreting linguistic input in real time depended on the relative engagement status of cognitive control, as determined by the prior Stroop trial type (see also Thothathiri et al., 2018).

While suggestive, the Hsu and Novick (2016) study leaves open two important issues. First, is conflict-driven cognitive control a better explanation than any other mechanism for what facilitates sentence revision? That is, incongruent Stroop trials are challenging and presumably result in multiple types of cognitive engagement beyond conflict detection and adjustments in behaviour. Indeed, incongruent Stroop items recruit the brain's multiple demand system (including the LIFG), which identifies a set of regions that engage across a wide variety of tasks as they become more difficult (Fedorenko et al., 2013). Thus, it remains possible that listeners' revision was enhanced by the effortful attention demands imposed by "tricky" Stroop items, rather than regulated behaviour triggered by conflicting representations per se. The adjustment of thoughts and actions that follow conflict detection (e.g. to bias processing away from a dominant characterisation of some stimulus) is hypothesised to occur at the level of internal representations (hence the term cognitive control), not because of exogenous shifts in attention (Botvinick et al., 2001; Kan et al., 2013).

Second, the Hsu and Novick (2016) study employed a verbal task (Stroop), raising questions about whether conflict detection stemming from a non-verbal source engages domain-general cognitive-control functions that also carry over to syntactic revision. Such cross-task adjustments in control would determine whether non-linguistic mechanisms also impact the language processing system and would provide compelling evidence for domain-general involvement in (re)interpretation procedures. One prior finding does show that the experience of perceptual conflict (ambiguous Necker cube) affects subsequent performance on a verbal-conflict task (Stroop), suggesting that domain-general cognitive control mediates conflict-adaptation effects (Kan et al., 2013). This result may be consistent with the co-localized LIFG recruitment for Stroop and visually degraded text during a reading task (van de Meerendonk et al., 2013). Yet the extent to which non-verbal, perceptual ambiguity engages cognitive control and impacts real-time sentence comprehension in a causal way is an empirical question.

Cognitive control and revising sentence misinterpretations: a domain-general process?

The various findings summarised thus far suggest that the ability to recover from misinterpretation draws on a shared mechanism that resolves conflict during syntactic, non-syntactic, and even perceptual tasks when conflicting representations develop from a linguistic source. Other data show that these effects extend beyond verbal boundaries, suggesting that the system that handles syntactic revision also handles non-verbal conflict. For example, in one neuroimaging study, participants completed a visual cognitive-control task, Flanker, in which they had to respond to the direction of a central arrow that was surrounded by arrows either pointing in a conflicting direction (e.g. →→←→→) or the same direction (e.g. →→→→→). Participants also completed a reading task that involved resolving conflict between representations of sentence meaning. Replicating the neuroimaging findings reviewed earlier, co-localized activity was observed within the LIFG for both types of conflict, suggesting that this region responds to non-verbal conflict in a manner similar to how it responds to verbal (and clearly, syntactic) conflict (Ye & Zhou, 2009). Consistent with this, behavioural measures of children's syntactic revision failure correlates with their Flanker performance (Woodard et al., 2016). Together, these findings provide evidence that domain-general cognitive control supports syntactic revision: a common process that similarly adjusts representations of linguistic and nonlinguistic input, agnostic to how the cognitive conflict originates (e.g. Miller & Cohen, 2001; Rajah et al., 2008).

But in fact, other data suggest a more conservative carving between verbal and non-verbal cognitive control, in line with a traditional distinction in executive function research in which separate systems handle each type of material (e.g. Shah & Miyake, 1996). Individual differences research that tests for a relationship between cognitive control and language processing bears this out to some extent. For instance, while verbal Stroop performance correlates with adults' ability to revise misinterpretations (Brown-Schmidt, 2009; Mendelsohn, 2002; Vuong & Martin, 2011), non-verbal Stroop performance does not (Brown-Schmidt, 2009; Vuong & Martin, 2011). This dissociation reflects a similar one seen in LIFG patients, whose non-verbal conflict resolution skills remain intact whereas their verbal conflict resolution skills are impaired (Hamilton & Martin, 2005). Such results deliver persuasive evidence for a domain-specific relationship between cognitive control and language processing that cleaves to a verbal/non-verbal boundary. Thus, in view of the mixed findings, one question that remains is the extent to which the ability to recover from syntactic misanalysis is assisted by a cognitive-control system that operates across verbal and nonverbal domains.

Experimental prospectus

Here, we test two open questions: Does engagement of more general, non-verbal cognitive-control mechanisms causally impact syntactic revision? Is the ability to revise facilitated by conflict-control procedures specifically, or is it better explained by increases in focused attention that arise with any increase in task difficulty? We will address these issues by using a cross-task functional-adaptation paradigm (Hsu & Novick, 2016; Kan et al., 2013; Thothathiri et al., 2018) that examines the effects of relative cognitive-control *states* on language comprehension, rather than cognitive-control *traits* that are the focus of investigation in large-scale individual differences research. To this end, we vary the properties of cognitive engagement (e.g. conflict-driven cognitive control vs. across-trial attention) from nonverbal stimuli during a previous trial and examine its immediate impacts on syntactic revision of early-arriving cues that were initially misanalysed. This will (a) isolate the specificity of conflict-driven cognitive-control effects on syntactic parsing and (b) determine if such effects are domain-general.

The methodological approach employed in this set of studies enables probing of the specific cognitive mechanisms that underlie real-time sentence revision. By manipulating the nature of the tasks that precede sentence comprehension trials requiring revision, we can examine the temporal dynamics between cognitive-control engagement and recovery from misinterpretation in a way that correlations cannot. Moreover, as will become evident below, the nature of the stimulus representations on preceding trials (e.g. arrow arrays) are radically different from those built during real-time parsing. Nevertheless, if these competing representations affect language processing, it would strongly suggest the mobilisation of domain-general cognitive-control processes that operate on a range of domain-specific representations (Experiments 1 and 3). And if these representations are adjusted to remove conflict on the prior trial (but still manipulate difficulty; Experiments 2 and 4), and we observe no reliable carryover, then this would support a process-specific component to the cognitive control and parsing account. Together, the results will advance our understanding of the mental architecture that supports language comprehension and could thus contribute insights into how to remediate language impairments in populations with poor cognitive control (Novick et al., 2009; Vuong & Martin, 2011).

Experiment 1

We hypothesise that conflict resolution via cognitive control is a domain-general process that facilitates listeners' ability to revise syntactic misinterpretations in real time. Thus, cognitive-control engagement from a non-verbal Flanker task should assist adults' syntactic revision in the same way as Stroop (Hsu & Novick, 2016), consistent with conflict-adaptation phenomena. This prediction is based on the finding that both Flanker and syntactic-conflict tasks result in co-localized LIFG recruitment within individual participants (Ye & Zhou, 2009), and that young children's Flanker performance correlates with revision abilities (Woodard et al., 2016). These patterns suggest a domain-general mechanism used for both non-verbal conflict resolution and sentence revision, but a direct, temporally close relation remains untested. Importantly, this link should dissolve when language processing does not require reinterpretation (e.g. unambiguous sentences like example 2), or when cognitive control is not engaged (e.g. prior Flanker trial does not involve conflict).

Method

Participants

Twenty-six right-handed adults (9 men, 17 women; mean age = 20.5 years, range = 18–27 years) were paid $10 per hour for participating. An a priori power analysis was conducted using the simr R package (v.1.0.5) for multilevel models (Green & MacLeod, 2016) and based on the results of Hsu and Novick (2016), which used a similar experimental design. Twenty-six participants were determined to have more than 90% power to detect a significant previous-by current-trial-type interaction in a new sample. This sample size is also in line with those in previous related studies (e.g. Chambers et al., 2004; Hsu & Novick, 2016; Thothathiri et al., 2018; Trueswell et al., 1999).

All participants were healthy, native monolingual speakers of English, were not taking any psychoactive medications, had no history of neurological disorders, had normal or corrected-to-normal vision, and were not colour blind. Participants provided written informed consent, and the human subjects review board at the University of Maryland approved all experimental procedures.

Materials and procedure

To examine whether non-verbal conflict detection engages cognitive control that subsequently eases syntactic revision, we pseudorandomly interleaved trials from an arrow Flanker task with a language-comprehension task. In the language-comprehension task, participants listened to a sentence that instructed them to perform an action involving objects on a computer screen (see Figure 2A). The syntactic structure of the sentence was either temporarily ambiguous or unambiguous using the "Put" materials as described in examples 1 and 2 respectively. Participants used a computer mouse to execute the instructions by dragging and dropping relevant objects around the display. Each critical sentence followed a Flanker task in which a central arrow's direction was either congruent or incongruent with the direction of surrounding arrows. All stimuli were presented using Experiment Builder software (Version 1.10.1630; SR Research, Kanata, Ontario, Canada).

Flanker task. In the Flanker task, participants clicked one of the mouse buttons to indicate whether an arrow located in the centre of the computer screen faced left or right. Flanking arrows faced the same direction as the centre arrow on 60 congruent trials (no-conflict) and faced the opposite direction of the centre arrow on 60 incongruent trials (conflict). On each Flanker trial, the mouse cursor appeared in the centre of the screen for 500 ms. The cursor was then replaced by the Flanker stimulus, remaining on the screen for 1000 ms or whenever the participant responded, whichever came first. Participants practiced a block of 96 Flanker-only trials (conflict and no-conflict items in equal proportion) at the beginning of the session before starting the main experiment.

Language comprehension task. Participants carried out spoken instructions, prerecorded by a female speaker, by dragging objects around a visual scene on

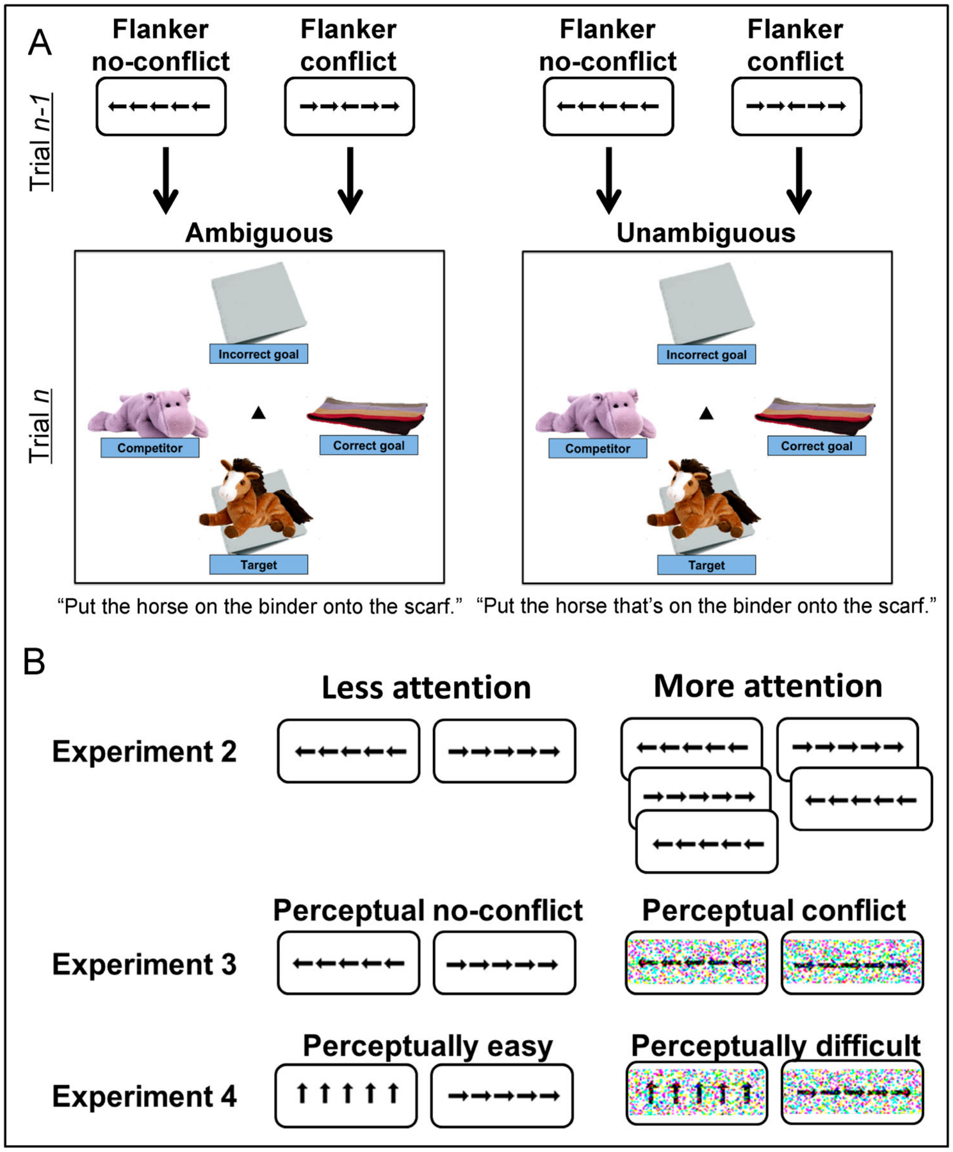

Figure 2. (A) Experimental design. In Experiment 1, Flanker conflict or no-conflict items could precede either ambiguous or unambiguous sentences. Visual scenes contained, for example, a horse on a binder (target), an empty binder (incorrect goal), a scarf (correct goal), and a hippo (competitor). Scenes therefore always corresponded to visual contexts that supported the goal analysis of "on the binder". (B) Examples of arrow stimuli used for Trial *n*-1 for Experiments 2–4. In Experiments 2–4, the Flanker task was replaced with another arrow task that manipulated attention (Experiment 2), perceptual conflict (Experiment 3), or perceptual difficulty (Experiment 4); see text for details.

a computer display. For example, they heard single commands like those in examples 1 and 2, repeated here:

1. Put the horse on the binder onto the scarf. (Temporarily Ambiguous)
2. Put the horse that's on the binder onto the scarf. (Unambiguous)

Scenes that accompanied the instructions contained a target referent (e.g. horse on a binder), a nontarget competitor (e.g. hippo), the correct goal (e.g. scarf), and an incorrect goal (e.g. empty binder). In example 1, the late-arrival of the prepositional phrase "onto the scarf" signals the goal of "Put … ", which conflicts with listeners' early preference to characterise "on the binder" as the goal first. Such conflict is removed in example 2 by inserting the complementizer "that's", which forces the modifier interpretation of "on the binder". In sentences like example 1 then, listeners must revise. Compared to sentences like 2, they exhibit some confusion until the correct-goal word is specified (e.g. " … scarf"), looking around the display before their eyes eventually land on the correct goal (e.g. the scarf).

Participants heard 24 ambiguous, 24 unambiguous, and 48 filler sentences that all involved "Put" commands. To obscure our manipulation and deter participants from learning that post-nominal prepositional phrases (e.g. "on the binder") might always be reduced relative modifiers, we designed filler items whose scenes visually resembled critical trials (like Figure 2), but whose instructions contained a post-nominal locative prepositional phrase (e.g. "Put the cow on the sweater", where the sweater is the correct goal). Importantly, this design feature should minimise the likelihood that participants would generally expect reduced relative constructions throughout the experiment (Fine et al., 2013). Therefore, they should not adopt a strategy of avoiding looking at the first empty object uttered in an instruction (e.g. incorrect goals like a binder) because this tactic would be incorrect for half the sentences in the experiment. Finally, because filler sentences followed Flanker items in the same way that ambiguous and unambiguous sentences did, there were no predictive relationships between Flanker trial-type and current sentence-type, namely whether binders or scarves or plates (for instance) would be the correct or incorrect goals.

Participants pressed the left mouse button to pick up, drag, and release objects around the scene. We counterbalanced item locations (i.e. target, competitor, incorrect goal, correct goal) within and across conditions. We created two lists that counterbalanced sentence ambiguity within items: if an item was ambiguous in one list, it was unambiguous in its corresponding list. Participants were randomly assigned to a list, with equal numbers of participants across lists.

On each sentence trial, the mouse cursor appeared in the centre of the screen for 500 ms to serve as a fixation point. All objects in the display then simultaneously appeared around the cursor. After a 300-ms delay, participants heard the spoken instruction. They could not move the mouse cursor to follow the instruction and perform an action until the sentence finished. A digital camcorder was placed by the participant's shoulder to film the computer screen and record drag-and-drop mouse-actions.

We monitored eye movements with an Eyelink 1000 eye-tracker (SR Research; temporal resolution: 1000 Hz, spatial resolution: $\leq 1.5°$) to obtain fine-grained measures of listeners' ongoing interpretation commitments as critical "Put" instructions unfolded in time (Tanenhaus et al., 1995). Thus, we could test whether listeners' ability to revise incorrect processing decisions moment-by-moment changed as a function of the prior Flanker-trial type, which determined whether cognitive control was relatively engaged (conflict trials) or not (no-conflict trials).

Interleaved Flanker-to-sentence sequences. To test whether detecting Flanker-conflict triggers cognitive-control mechanisms that immediately influence listeners' ability to revise, we interspersed Flanker trial types and language-comprehension trial types pseudorandomly to create a 2×2 design: conflict or no-conflict Flanker items (trial *n*-1) preceded either ambiguous or unambiguous sentences (trial *n*). Participants completed 48 critical Flanker-Sentence pairs: 12 No-Conflict-Unambiguous pairs; 12 Conflict-Unambiguous pairs; 12 No-Conflict-Ambiguous pairs; and 12 Conflict-Ambiguous pairs. These sequences were embedded within a larger experimental context that also contained 48 filler sentences and 72 additional Flanker trials, so that there were several Sentence-to-Sentence and Flanker-to-Flanker sequences, thus preventing participants from predicting upcoming trial or even task type. The design was therefore identical to that of Hsu and Novick (2016) in all ways except that Stroop was exchanged for Flanker (for similar designs, see Adler et al., 2019; Kan et al., 2013; Thothathiri et al., 2018).

Data analysis

For the Flanker task, we collected accuracy and response time (RT) data. For the language-comprehension task, we collected mouse-action data as a measure of listeners' offline, final interpretations, and eye-movement data as a measure of online processing. Following earlier studies (e.g. Hsu & Novick, 2016; Novick et al., 2008; Trueswell et al., 1999; Woodard et al., 2016), we coded actions as correct if participants used the mouse to drag the target from its original location (e.g. horse on a binder) directly to the correct goal (e.g. the scarf). If the mouse moved from the original location directly to the correct goal (even if the target did not move), those were also coded as correct, as the mouse movements made clear the participant's intention to move the target from its original location directly to the correct goal. We coded actions as incorrect if the false goal (e.g. the empty binder) was included in any action, such as moving the target horse to the empty binder and leaving it there, or moving it to the empty binder first before the scarf (the correct goal).

For eye movements, we labelled each screen quadrant (e.g. top, bottom, left, right) as an interest area, and used this labelling to generate sample reports from the EyeLink Data Viewer tool (Version 2.3.22; SR Research) to determine fixation proportions. For all eye-movement data, we shifted the windows of analysis by 200 ms (e.g. following the offset of "scarf") to allow for the time it takes to launch an eye movement after it has been programmed (Matin et al., 1993). We also excluded any trials with more than 33% loss in eye-tracking data (e.g. due to excessive blinks, etc.). This meant excluding 4–7% of the dataset across all four experiments.

We used paired *t*-tests to analyze the behavioural data from the Flanker task. Eye-movements and hand-actions from the language-comprehension task were analysed using the lme4 statistical software package (Bates et al., 2015) in the R programming environment (R Development Core Team, 2014). We fit mixed-effects logistic regression models with a random effects structure as follows: We first tested a full model that included both random slopes and intercepts. If a model containing the random slopes did not differ significantly from one without random slopes, then the random slopes were removed for subsequent models. The same logic was applied to random intercepts. We also included items and participants as random effect intercepts and current sentence-trial type (ambiguous as reference), previous Flanker-trial type (no-conflict as reference), and their interaction as fixed effects. We used these models to predict (a) the accuracy of action responses (final interpretations); and (b) the proportion of looks to the correct goal (indicating real-time revision of an initial misinterpretation). For hand-action and eye-movement analyses, we performed a likelihood ratio test to compare the fit of models that included the interaction term against those that did not, and therefore report χ^2 values. Models are considered significant at $p \leq .05$. We will not interpret data that fails to meet this threshold.

Results

Flanker task manipulation check

To determine first whether our Flanker manipulation induced conflict as expected, we analysed Flanker RT data for correct trials only (97.8% of the full dataset). As can be seen in Figure 3A, conflict trials elicited slower responses than non-conflict trials. This

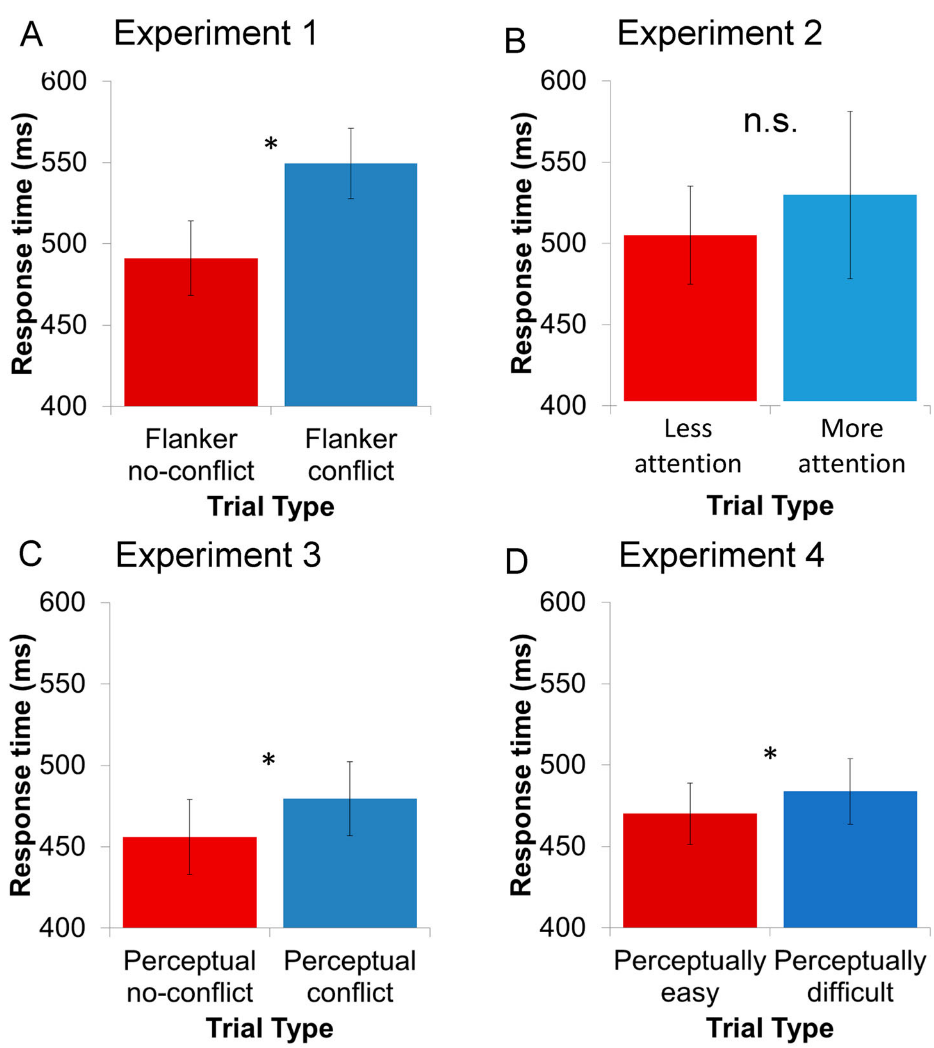

Figure 3. Response time on correct *n*-1 (e.g. Flanker) trials across experiments: (A) Experiment 1; (B) Experiment 2; (C) Experiment 3; (D) Experiment 4. * indicates $p \leq .05$. Error bars indicate 95% confidence interval.

observation was confirmed using a paired samples *t*-test: Participants were significantly slower to respond to conflict ($M = 549$ ms, *95% CI* = [528, 571]) than no-conflict trials ($M = 491$ ms, *95% CI* = [468, 514]; $t(25) = 11.61$, $p < .001$, Cohen's $d = 0.99$), replicating the classic Flanker effect.

Signs of misinterpretation: syntactic ambiguity manipulation check

Next, to determine whether listeners temporarily misinterpreted on ambiguous trials as expected, we calculated looks to the incorrect goal (e.g. the empty binder) while hearing conflicting evidence (e.g. "onto the"), namely the time window right after participants heard the incorrect-goal word (e.g. "on the binder"). As seen in Figure 4A, participants looked more to the incorrect goal under ambiguous compared to unambiguous conditions during this interval. This was confirmed by a mixed-effects model with current trial-type as a fixed effect (unambiguous: $M = .13$, *95% CI* = [.10, .15]; ambiguous: $M = .18$, *95% CI* = [.16, .21], $\chi^2(1, N = 26) = 6.64$, $p = .01$, estimated effect of −5.1%, standardised effect size of 0.17). This pattern replicates previous studies using these stimuli: for ambiguous sentences, listeners initially misinterpreted the first prepositional phrase (e.g. "on the binder") as a goal, and must revise according to new, conflicting input ("onto the scarf").

Effect of Flanker conflict on off-line revision (mouse-actions)

Participants were more accurate on unambiguous sentences ($M = .96$, *95% CI* = [.94, .99]) than ambiguous sentences ($M = .90$, *95% CI* = [.86, .94]; $\chi^2(1, N = 26) = 6.90$, $p = .009$, estimated effect of +6.6%, standardised effect size of 0.26). In other words, listeners made reliably more errors involving the incorrect goal under

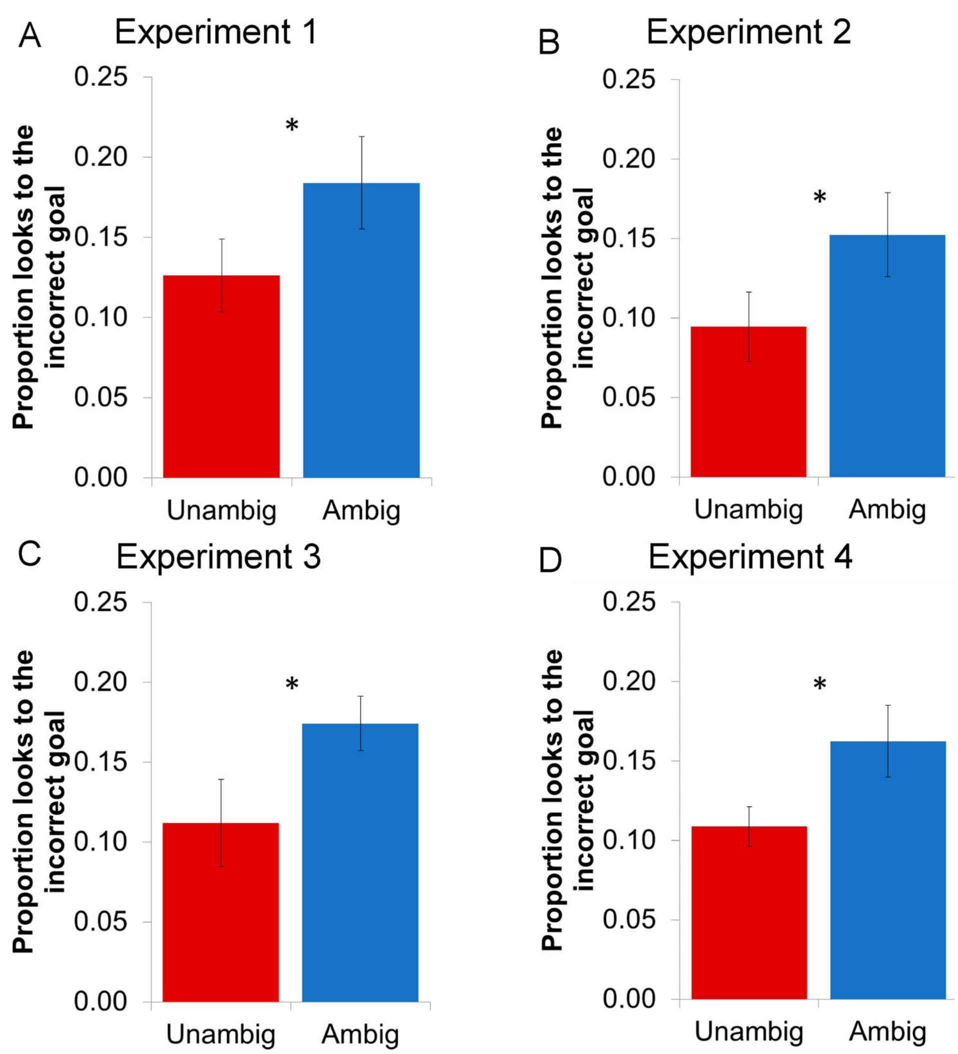

Figure 4. Proportion of looks to the incorrect goal for the language-comprehension task during "onto the" time window (see text), across all four experiments. Experiment 1 (A), Experiment 2 (B), Experiment 3 (C), and Experiment 4 (D). * indicates $p \leq .05$. Error bars indicate 95% confidence intervals.

ambiguous conditions, indicating that they sometimes failed to revise. Did the manipulation of prior Flanker-trial type, and thus cognitive-control engagement, modulate this pattern? As can be seen in Figure 5A, participants were more accurate for ambiguous sentences that followed Flanker-conflict compared to no-conflict trials, but the Flanker manipulation did not influence performance on unambiguous sentences. This pattern is consistent with conflict adaptation. A significant Previous × Current Trial-Type Interaction confirmed these observations ($\chi^2(1, N = 26) = 4.43$, $p = .035$, estimated effect of +9.9%, standardised effect size of 0.39). Specifically, participants performed more correct actions on Conflict-Ambiguous sequences ($M = .95$, *95% CI* = [.92, .98]) than on No-Conflict-Ambiguous sequences ($M = .84$, *95% CI* = [.78, .90]; $\chi^2(1, N = 26) = 5.34$, $p = .02$, estimated effect of +10.6%, standardised effect size of 0.41). There was no difference in action responses for Conflict-Unambiguous and No-Conflict-Unambiguous sequences ($p > .05$). Together, this suggests that cognitive-control engagement from a non-verbal, visual source can mitigate errors in language comprehension.

Effect of Flanker conflict on on-line revision (eye movements)

Our measure of online revision is looks to the correct goal, e.g. the scarf (Hsu & Novick, 2016; Novick et al., 2008; Woodard et al., 2016). Informal inspection of the eye-movement data (see Figure 6) suggests that upon hearing the onset of the correct-goal word (e.g. "scarf"), listeners first looked overwhelmingly to the target (e.g. horse on binder) in both Ambiguous and Unambiguous conditions until the offset of the correct-goal word, when looks to the correct goal began to increase and target looks began to decrease. As can be seen though, in an 800-ms time interval following "scarf" offset, looks to the correct goal are overall lower (and looks to the target are higher) in ambiguous compared to unambiguous conditions. This reflects listeners' delay integrating the correct-goal word (e.g. "scarf") with their current misinterpretation (e.g. empty binder as goal). Therefore, we analysed the proportion of fixations on the correct goal in this 800-ms interval, to test the extent to which prior Flanker-type influenced the time-course of revision processes.

To pinpoint effects that emerged specifically following the onset of conflicting evidence, we analysed fixations that occurred only *after* hearing disambiguating cues (i.e. "onto the … "). We divided trials on the basis of whether a participant was already looking at the correct goal (e.g. the scarf) just before hearing disambiguating information. For those trials when listeners were *not* already looking at the correct goal, we calculated the probability of switching *to* the correct goal as a "pure" measure of revision. This approach allowed us to factor out early differences in fixation patterns on

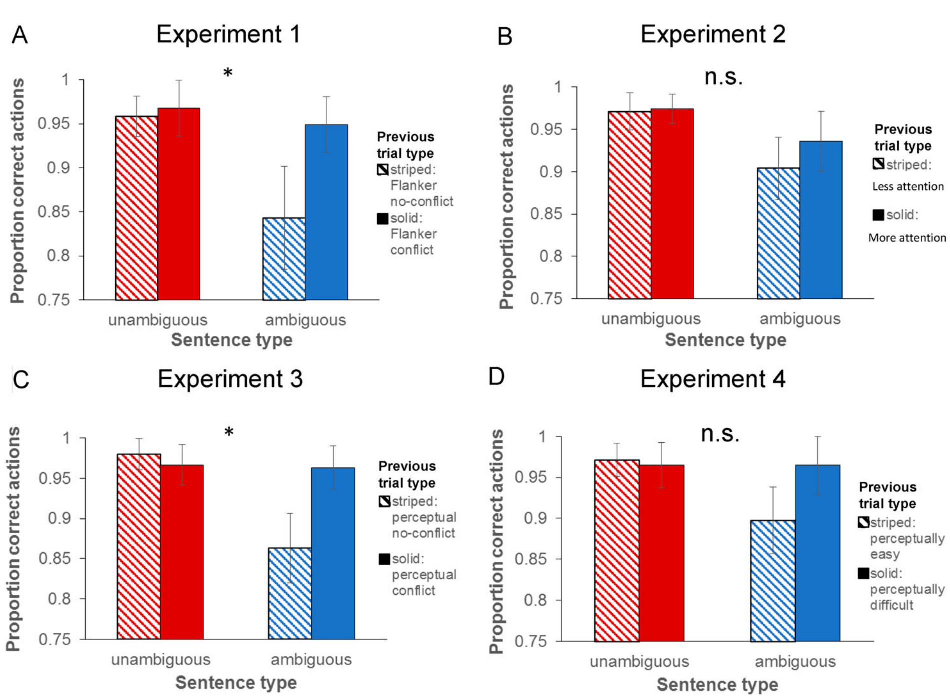

Figure 5. Proportion of correct actions (e.g. moving the target directly to the correct goal) for current trial type as a function of previous trial type across all experiments. Experiment 1 (A), Experiment 2 (B), Experiment 3 (C), and Experiment 4 (D). * indicates $p \leq .05$. Error bars indicate 95% confidence intervals.

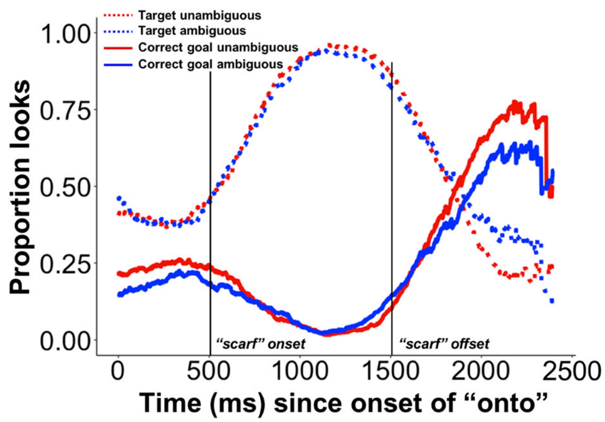

Figure 6. Proportion target and correct-goal looks over time, following the onset of disambiguating evidence (e.g. "onto … ").

the correct goal that could not actually be explained by hearing "onto the scarf" (for other work employing such "switch" analyses, see Fernald et al., 1998; Huang & Snedeker, 2009; Swingley & Fernald, 2002; see also Altmann & Kamide, 2004). Thus, we report only correct-goal fixations that *could be* accounted for by hearing relevant disambiguating evidence.

Figure 7A plots the proportion of looks to the correct goal in the 800-ms time window following the offset of "scarf". As can be seen, listeners looked more to the correct goal in this interval when ambiguous sentences followed Flanker-conflict trials, compared to no-conflict trials. Fixations on the correct goal during unambiguous sentences appeared not to be affected by previous trial type. These observations were confirmed by a Previous × Current Trial-Type Interaction ($\chi^2(1, N = 26) = 3.83$, $p = .05$, estimated effect of +14.5%, standardised effect size of 0.30). This interaction emerged because prior Flanker-type modulated consideration of the correct goal under ambiguous (but not unambiguous) conditions (Flanker-conflict-ambiguous: $M = .463$, *95% CI* = [.395, .530]; Flanker no-conflict-ambiguous: $M = .393$, *95% CI* = [.337, .449]; $p = .005$). When analysing only correct-action trials, this interaction pattern was in the same direction as the overall effect ($\chi^2(1, N = 26) = 2.99$, $p = .08$, estimated effect of +12.4%, standardised effect size of 0.26), though non-significant. In sum, the prior detection of Flanker-conflict engaged cognitive control and assisted listeners' real-time revision of incorrect processing commitments.

Discussion of Experiment 1

One goal of Experiment 1 was to test if conflict adaptation is observable from a non-verbal to a syntactic domain. As hypothesised, cognitive-control engagement from a visual Flanker task facilitated adults' syntactic revision in the same manner as earlier research employing a verbal Stroop task (Hsu & Novick, 2016; see also Navarro-Torres et al., 2019 for a replication). Off-line mouse-actions revealed that listeners' final interpretations of ambiguous sentences were reliably more accurate when preceded by Flanker-conflict compared to no-conflict trials. This suggests that cognitive-

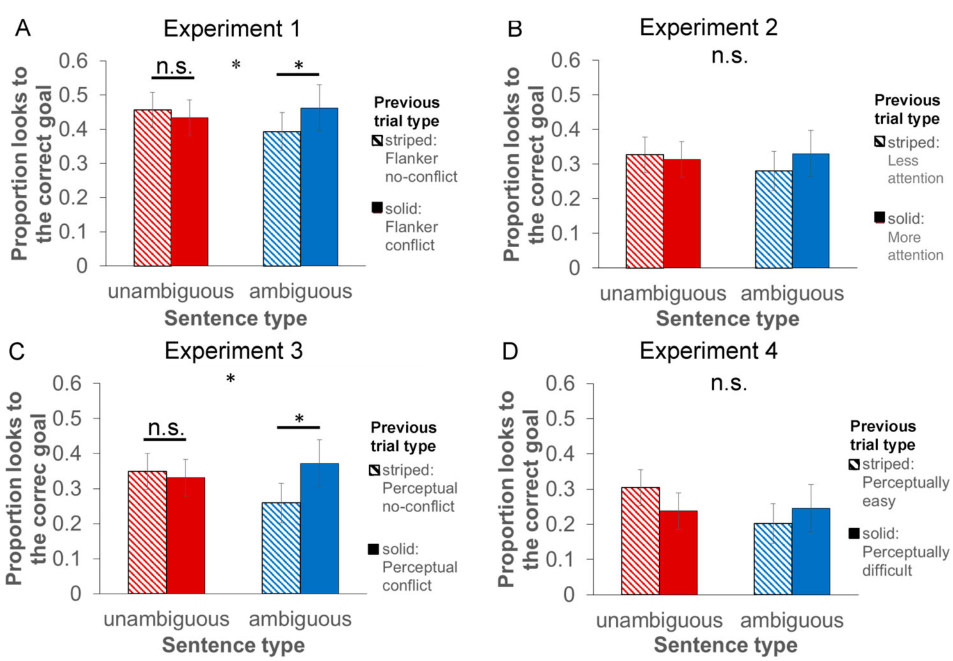

Figure 7. Proportion of looks to the correct goal, during an 800-ms window following the offset of hearing correct-goal specification (e.g. "scarf"). * indicates $p \leq .05$. Error bars indicate 95% confidence intervals.

control engagement, even from a non-verbal source, can penetrate the language-processing system to modulate revision procedures and prevent comprehension errors in a causal way. On-line eye-movements also revealed that revision occurred earlier: soon after hearing the correct-goal word (e.g. "scarf"), listeners fixated on the correct goal more when Flanker-conflict trials preceded ambiguous sentences, indicating that deploying cognitive-control processes impacts the ease with which they revise syntactic misanalyses in real time. Importantly, this causal link vanished when language processing did not require revision (i.e. under syntactically unambiguous conditions), or when cognitive control was not engaged (i.e. when prior Flanker trial did not involve conflict). These results suggest a direct and near-immediate impact of domain-general cognitive-control engagement on sentence revision.

However, like Stroop-conflict, Flanker-conflict may engage other cognitive mechanisms (e.g. maintaining attention across the duration of the trial) that mobilise under difficult conditions. It is therefore possible that listeners' revision was assisted by increases in attention demands that arose from more effortful Flanker items. We address this in Experiment 2.

Experiment 2

The current experiment tests whether the observed cross-task effects on revision in Experiment 1 indeed reflect adaptation to conflict – namely, the engagement of cognitive control (e.g. Botvinick et al., 2001) – or whether the patterns merely reflect heightened arousal or attention, such as those involved in initiating or sustaining task goals (Petersen & Posner, 2012). If the results of Experiment 1 can be ascribed to modulations in attention, then when we manipulate attention on the prior trial, the carry over effects should replicate under conditions of increased attention. However, if the results of Experiment 1 are due to conflict-driven cognitive control, then there should not be the same degree of carry over when conflict is removed on the prior trial (when attention, not cognitive control, is engaged).

We hypothesise that for revision to occur, a stimulus must induce an experience of internal representational conflict that in turn initiates cognitive-control mechanisms to (re)bias processing. That is, simply "paying more attention" or being overall more engaged due to difficulty then should have limited effects on syntactic revision. Here, we manipulate listeners' attention across the duration of the stimulus on a prior trial and predict that this modulation should not influence language comprehension on subsequent trials as much as conflict-driven cognitive control (Exp. 1), because the task does not involve conflicting representations (hence no cognitive-control engagement). Such a finding would suggest that conflict-driven cognitive-control effects on sentence revision are more than just broad increases in attention across a trial during a hard task. Indeed, prior work indicates that exogenous effort (e.g. tracking how many times an unambiguous cube flips direction) is insufficient to confer conflict adaptation to a Stroop task (Kan et al., 2013).

Method

Participants

Twenty-six right-handed adults (4 men, 22 women; mean age = 20.7 years, range = 18–25 years) who did not participate in Experiment 1 were paid $10 per hour. All participants were healthy, native monolingual speakers of English, were not taking any psychoactive medications, had no history of neurological disorders, had normal or corrected-to-normal vision, and were not colour blind. They provided written informed consent, and the human subjects review board at the University of Maryland approved all experimental procedures.

Materials and procedure

Experiment 2 was methodologically identical to Experiment 1 except that we replaced the Flanker task with a prolonged-attention task that varied task engagement demands on trial *n*-1. This task did not involve representational conflict but did use arrow displays to keep the stimulus types consistent across experiments.

Prolonged-attention task. Participants used the mouse buttons to indicate whether a display of five arrows (same number as in the previous Flanker task; see Figure 2B) located in the centre of the computer screen faced left or right. The arrows always pointed in the same direction on a given trial, hence no conflict. In one condition ("less attentionally demanding"), the arrow stimuli remained on the screen for 1000 ms. Participants simply indicated by mouse-press the arrows' direction. To manipulate attention, in another condition ("more attentionally demanding"), the arrows remained on the screen for variable amounts of time (depending on the trial) that lasted anywhere from 2000 to 21,000 ms (average: 10,000 ms). During such trials, the group of arrows flipped direction (e.g. from all pointing leftward, to all pointing rightward) anywhere from 1 to 3 times over the course of a trial. Just as in the "less attentionally demanding" condition, participants indicated whether the arrows faced left or right, and they pressed a mouse button for every flip to indicate the arrows' new direction (for a similar design, see Kan et al., 2013). This condition required participants to continuously attend to the task because how often and when a flip would occur was unpredictable within and across trials. Note that, if participants are truly attending throughout each trial, there may not be any significant behavioural differences between more and less attentionally demanding conditions as people maintain prolonged attention during the more difficult trials (Kan et al., 2013), though RTs in the more attentionally demanding condition may be nominally higher (Lorist et al., 2000). Participants practiced a block of 96 trials (less and more attentionally demanding items in equal proportion) at the beginning of the session before starting the main experiment.

Results

Prolonged-attention task manipulation check

We analysed RT data for correct trials only. For "more attentionally demanding" trials, this reflected the time to respond to the last arrow stimulus presented in the trial (i.e. after all flips). In this condition, correct trials were those whose number of button-presses matched the number of arrow presentations in the trial (i.e. tracking accuracy; Kan et al., 2013), or 81.9% of the full dataset. In the "less attentionally demanding" condition, this included 94.3% of the dataset (NB: these error rates, 18.1% vs. 5.7%, were reliably different; $p = .001$, suggesting greater difficulty in the more-demanding condition). As seen in Figure 3B, participants took nominally longer to respond to "more attentionally demanding" trials ($M = 530$ ms, *95% CI* [478, 581]) than "less attentionally demanding" trials ($M = 505$ ms, *95% CI* = [475, 535]), but this difference was not statistically reliable ($t(25) = 1.54$, $p = .14$, Cohen's $d = 0.23$). This pattern of behavioural results suggests that, minimally, participants kept pace with the timing of the arrow switches and did not exhibit a speed-accuracy trade-off in the more demanding vs. less demanding condition. It therefore appears that participants were following task instructions on the hard task, i.e. they maintained their speed over the course of the "more attentionally demanding" trials when they were doing the task correctly (Kan et al., 2013; Lorist et al., 2000).

Signs of misinterpretation: syntactic ambiguity manipulation check

As seen in Figure 4B, participants looked more to the incorrect goal during ambiguous ($M = .15$, *95% CI* = [.13, .18]) compared to unambiguous sentences ($M = .09$, *95% CI* = [.07, .12]; $\chi^2(1, N = 26) = 9.70$, $p = .002$, estimated effect of −7.4%, standardised effect size of 0.23). Thus, replicating Experiment 1, listeners temporarily misinterpreted the first prepositional phrase.

Effect of prolonged attention on off-line revision (mouse-actions)

Like Experiment 1, we found an ambiguity effect: participants were more accurate on unambiguous ($M = .97$, *95% CI* = [.96, .99]) compared to ambiguous sentences ($M = .92$, *95% CI* = [.89, .95]; $\chi^2(1, N = 26) = 9.08$, $p = .003$, estimated effect of +5.3%, standardised effect size of 0.23). However, unlike Experiment 1, the prior trial type that manipulated attentional demands across the trial did not modulate this pattern (see Figure 5B): there was no Previous × Current Trial-Type Interaction ($\chi^2(1, N = 26) = 0.71$, $p = .40$, estimated effect of +2.9%, standardised effect size of 0.13). Thus, we did not find evidence to support the notion that broad attention by itself impacts recovery from misinterpretation in the same way as cognitive control.

Effect of prolonged attention on on-line revision (eye movements)

We analysed eye movements in exactly the same way as Experiment 1, as fixation patterns over time between the two studies were remarkably similar. Figure 7B plots the proportion of looks to the correct goal in the 800-ms time window following the offset of "scarf". As can be seen, listeners did not look more to the correct goal in this interval when ambiguous sentences were preceded by more attentionally-demanding arrow trials, compared to less-demanding ones. Fixations on the correct goal during unambiguous sentences also appeared not to be affected by previous trial type. Indeed, unlike Experiment 1, we did not find a significant Previous × Current Trial-Type Interaction ($\chi^2(1, N = 26) = 2.26$, $p = .13$, estimated effect of +8.1%, standardised effect size of 0.18). When accounting for only correct mouse-action trials, the interaction was still absent ($\chi^2(1, N = 26) = 1.75$, $p = .19$, estimated effect of +7.1%, standardised effect size of 0.15).

Discussion of Experiment 2

Previous research has shown that exogenous manipulations of attention to task stimuli, short of conflicting representations, are insufficient to account for conflict-adaptation effects (Kan et al., 2013). For trial-to-trial performance adjustments to occur, one must experience internal competition between incompatible interpretations of a stimulus, which sets cognitive-control processes in motion to bias processing toward task-relevant cues to resolve the conflict. The results of

Experiment 2 are fully consistent with this pattern, and further demonstrate that increased attentional demands, without conflict, are not enough to explain syntactic revision. Neither off-line nor on-line measures of revision were impacted by the attention manipulation on a prior trial. Alongside the results of Experiment 1, these findings suggest that revision is driven by the detection of conflicting representations per se and the engagement of domain-general cognitive-control mechanisms. Notably, the stimuli on preceding trials (arrow arrays) were the same across the two experiments. The difference in Experiment 2 was that we modified the representations to eliminate conflict and instead increase demands on attention. By and large, attention across the trial by itself may not explains adults' ability to recover from misinterpretations of language input.

But comparisons across Experiments 1 and 2 in online and offline data require some elaboration. First, the eye movement data to the correct goal, illustrated in Figure 7, shows that cognitive-control engagement reliably *increases* looks to the correct goal (our measure of real-time revision), whereas attention does not. This is as predicted. Similarly, the offline data suggests that the attention manipulation does not affect comprehension errors, whereas the cognitive control manipulation does (see Figure 5). However, inspection of these offline data in Figure 5 suggests that the differences across experiments appears largely in the no-conflict and less-attention conditions. That is, when comparing Experiments 1 and 2, for the ambiguous sentences, participants' performance appears less accurate after a no-conflict Flanker trial (Exp. 1) than a less attention trial (Exp. 2), while the differences between the conflict and the more-attention conditions are less obvious. Why this pattern? It is important to keep in mind that offline accuracy (e.g. moving the horse directly to the scarf, avoiding the incorrect goal) is routinely high in healthy adults (>90%). The striking point is that in the Ambiguous condition of Experiment 1, when the prior trial is Flanker no-conflict (cognitive control "off") – listeners make reliably *more* errors compared to when the prior Flanker trial contains conflict (cognitive control is "on"). Put another way, when cognitive control is relatively not engaged, even healthy adults misinterpret like patients with cognitive control deficits – they fail to revise with increased frequency. This is expected. In the attention manipulation, even when attention is relatively downregulated (striped bars in Figure 5, Exp. 2, ambiguous condition), listeners' comprehension is still more than 90% accurate. Namely, less vs. more attention does not affect people's ability to revise misinterpretations – only cognitive control seems to matter for ambiguity resolution. To preview, we will see this same pattern in the offline data comparison of Experiments 3 and 4.

One limitation to our general interpretation of Experiment 2 results is that the attentionally-demanding task included 1–3 responses and a longer stimulus duration than the cognitive-control task in Experiment 1, which could account for the predicted differences across experiments. Experiments 3 and 4 address this by equating the number of responses and stimulus durations while still varying cognitive control versus attention.

Experiment 3

Thus far, we have found that conflict-resolution engages cognitive-control procedures that facilitate syntactic revision (Experiment 1), and that these procedures are discernable from attention to task stimuli as a causal factor (Experiment 2). Moreover, sentence reinterpretation appears to be handled by a cognitive-control mechanism that ignores any separation between verbal and non-verbal stimuli, suggesting that cognitive control is a domain-general process that regulates representations of stimuli that are wildly dissimilar (e.g. arrows, spoken sentences). But how general is the process that impacts syntactic revision in a cause-and-effect way? As sketched in the Introduction, conflict monitoring theory claims that conflict can arise at multiple levels, from perceptual representations all the way up to response selection, all of which should trigger ensuing adjustments in control (Botvinick et al., 2001).

Logically then, another essential prediction of the cognitive control and parsing account is that visual-perceptual ambiguity should create representational conflict, which in turn should yield control adjustments that aid sentence reinterpretation akin to how Stroop- and Flanker-conflict do. Earlier work supports this prediction to some degree: cross-task adjustments in control are observed from a perceptual-ambiguity task to a verbal-conflict task (Kan et al., 2013); post-error behavioural adjustments are observed following words presented in auditory noise, which may generate more competitive lexical alternatives (Vaden et al., 2013); and perceptually degraded text, which produces underdetermined representations of sentence meaning, recruits the same LIFG regions as Stroop (van de Meerendonk et al., 2013). For example, Kan and colleagues (2013) showed that experiencing conflict from a perceptually bi-stable Necker cube produces cross-task conflict adaptation to a verbal Stroop task, suggesting that such behavioural adjustments are mediated by a broad cognitive-control mechanism. Likewise, behavioural adjustments have been observed when recognising words in noise, which creates perceptual ambiguity and underdetermined conflict. For example, greater activity in brain regions that support conflict detection on one trial predicts better word recognition on a subsequent trial (Vaden et al., 2013).

But whether non-verbal, perceptual ambiguity engages cognitive control and directly impacts recovery from misinterpretation in a causal way is still an open issue. Such a finding would provide strong evidence for a domain-general cognitive-control process that facilitates sentence revision. We test this hypothesis in the current experiment.

Method

Participants

Twenty-six right-handed adults (13 men, 13 women; mean age = 19.5 years, range = 18–23 years) who did not participate in Experiments 1 or 2 were paid $10 per hour. All participants were healthy, native monolingual speakers of English, were not taking any psychoactive medications, had no history of neurological disorders, had normal or corrected-to-normal vision, and were not colour blind. They provided written informed consent, and the human subjects review board at the University of Maryland approved all experimental procedures.

Materials and procedure

Experiment 3 was methodologically identical to Experiments 1 and 2 except that we replaced the Flanker and attention-demanding tasks with a task that varied perceptual ambiguity on trial *n*-1. This task also used arrow displays to keep the stimulus types consistent across experiments. Because of the introduction of perceptual ambiguity, we expected to reproduce the conflict adaptation patterns found in Experiment 1, extending prior findings showing cross-task adjustments from perceptual ambiguity to a verbal Stroop task (Kan et al., 2013).

Perceptual conflict task. Participants used a mouse to indicate whether a display of five arrows (same number as in the previous tasks; see Figure 2B) located in the centre of the computer screen faced left or right. The arrows always pointed in the same direction on a given trial. In one condition ("perceptual no-conflict"), the arrow stimuli remained on the screen for 1000 ms. Participants simply indicated by mouse-press the arrows' direction. Visual degradation of the arrows created conflict in another condition ("perceptual conflict"). Here, the arrow stimuli also remained on the screen for 1000 ms, but we applied a visual mask that made it harder to see the arrowheads' direction. Just as in the "perceptual no-conflict" condition, participants indicated whether the arrows faced left or right, but the mask generated a degree of perceptual ambiguity in this condition and thus underdetermined conflict between left-right representations of the arrow stimuli. There were 60 perceptual no-conflict and 60 perceptual-conflict items (see Experiment 1 method). For the conflict items, we created 30 left-facing and 30 right-facing visually-masked arrow images through the imnoise function in Matlab, utilising "salt and pepper" coloured noise at a density of 0.30 (pilot testing revealed that this density value achieved a moderate level of difficulty). Participants practiced a block of 96 trials (perceptual-conflict and perceptual no-conflict items in equal proportion) at the beginning of the session before starting the main experiment.

Results

Perceptual conflict manipulation check

We analysed RTs on correct trials only (96.8% of the full dataset). As seen in Figure 3C, participants were significantly slower to respond to Perceptual conflict (M = 479 ms, *95% CI* = [457, 502]) compared to Perceptual no-conflict trials (M = 456 ms, *95% CI* = [433, 479]; $t(25) = 7.60$, $p < .001$, Cohen's $d = 0.40$). Therefore, the visual mask elicited a reliable effect of ambiguity: the arrowheads were hard to perceive, creating underdetermined conflict as expected, akin to other perceptually bi-stable stimuli that induce conflict (Kornmeier & Bach, 2005; Long & Toppino, 2004).

Signs of misinterpretation: syntactic ambiguity manipulation check

As can be seen in Figure 4C, participants looked more to the incorrect goal during ambiguous (M = .17, *95% CI* = [.16, .19]) than unambiguous sentences (M = .11, *95% CI* = [.08, .14]; $\chi^2(1, N = 26) = 10.08$, $p = .002$, estimated effect of −6.7%, standardised effect size of 0.20). This effect replicates the ambiguity effects observed in Experiments 1 and 2, and indicates temporary misinterpretation of the first prepositional phrase.

Effect of perceptual conflict on off-line revision (mouse-actions)

As in Experiments 1 and 2, we observed an ambiguity effect, namely healthy adult listeners sometimes fail to revise: they were reliably more accurate on unambiguous (M = .97, *95% CI* = [.96, .99]) compared to ambiguous sentences (M = .91, *95% CI* = [.89, .95]; $\chi^2(1, N = 26) = 7.42$, $p = .006$, estimated effect of +5.8%, standardised effect size of 0.25). But did the manipulation of perceptual conflict, and thus cognitive-control engagement, modulate this pattern like in Experiment 1? As can be seen in Figure 5C, participants were more accurate for ambiguous sentences when the prior arrow trial involved perceptual conflict as opposed to no-conflict, but this manipulation seemed not to influence comprehension of unambiguous sentences. Crucially, like Experiment 1, we confirmed this observation with a significant Previous × Current Trial-Type Interaction ($\chi^2(1, N = 26) = 7.47$, $p = .006$, estimated effect of +11%, standardised effect size of 0.48). This interaction emerged because participants performed better on perceptual-conflict-Ambiguous sequences ($M = .96$, *95% CI* = [.94, .99]) as compared to perceptual no-conflict-Ambiguous sequences ($M = .86$, *95% CI* = [.83, .91]; $\chi^2(1, N = 26) = 6.24$, $p = .01$, estimated effect of +9.6%, standardised effect size of 0.42). We found no difference in action responses for perceptual-no-conflict-unambiguous and perceptual-conflict-unambiguous sequences ($p > .05$). Together, this suggests that even visual-perceptual ambiguity can engage cognitive-control processes that actually prevent errors in sentence comprehension.

Effect of perceptual conflict on on-line revision (eye movements)

We analysed eye movements in exactly the same way as Experiments 1 and 2, as fixation patterns over time were once again remarkably similar across the three studies. Figure 7C plots the proportion of looks to the correct goal in the 800-ms window following the offset of the correct-goal word (e.g. "scarf"). As can be seen, listeners looked more to the correct goal when ambiguous sentences were preceded by perceptual-conflict trials, compared to no-conflict trials. Fixations on the correct goal during unambiguous sentences were not affected by previous trial type. These observations were confirmed by a significant Previous × Current Trial-Type Interaction ($\chi^2(1, N = 26) = 5.55$, $p = .02$, estimated effect of +13.9%, standardised effect size of 0.30). Cognitive-control engagement modulated consideration of the correct goal under ambiguous (but not unambiguous) conditions (perceptual-conflict-ambiguous: $M = .372$, *95% CI* = [.321, .423]; no-conflict-ambiguous: $M = .259$, *95% CI* = [.217, .301]; $p = .002$). This interaction remained significant for just the trials when listeners carried out correct mouse-actions ($\chi^2(1, N = 26) = 4.14$, $p = .04$, estimated effect of +11.9%, standardised effect size of 0.25). Overall, these patterns suggest that the prior detection of perceptual-conflict engaged cognitive control, which assisted listeners' real-time revision of early cues that were initially misinterpreted.

Discussion of Experiment 3

The results of Experiment 3 demonstrate that visually degrading an arrow display created perceptual conflict, which made it harder to determine the direction that the arrows were pointing. This conflict triggered cognitive-control engagement that in turn facilitated syntactic revision. Mouse-action data showed that listeners made fewer comprehension errors involving the incorrect goal when ambiguous sentences followed visually degraded trials, as opposed to visually intact ones. On-line eye-movement data showed that such revision occurred earlier in time. In a temporal window soon after hearing correct-goal specification (e.g. "scarf"), listeners looked more to the correct goal when ambiguous sentences followed perceptual-conflict trials, as opposed to ones that did not involve perceptual conflict. This further supports domain-general conclusions: conflict detection that derives from a non-verbal, perceptual source mobilises cognitive-control functions that facilitate recovery from sentence misinterpretation. Combined with Experiment 1, we believe this provides strong evidence that cognitive control is a common process that operates over a variety of distinct representations, and suggests that it may be a causal factor in syntactic reanalysis. We view the cross-task effect here to be akin to the cross-task effects that Kan and colleagues found, from an ambiguous percept (Necker cube) to a verbal Stroop task (i.e. more conflict experienced during a Necker-cube trial yielded a smaller conflict effect on the Stroop trial; Kan et al., 2013).

Though these results may be surprising – why would arrowheads that are hard to see influence language comprehension? – they are fully consistent with conflict-monitoring theory and dual-stream accounts positing that control mechanisms occur in parallel (Botvinick et al., 2001; Marek & Dosenbach, 2018). The findings are also consistent with prior correlational patterns and conflict-adaptation phenomena. First, conflict-monitoring theory assumes that multiple underdetermined representations of a perceptual stimulus will initiate cognitive-control processes to mitigate the competition. Second, recall that processing visually degraded text co-localizes with Stroop in the LIFG, a region known to be involved in conflict-resolution and cognitive-control across a broad range of tasks (van de Meerendonk et al., 2013). In addition, detecting visual ambiguity (e.g. in the Necker cube) engages cognitive control, which attenuates the cost of processing subsequent Stroop conflict (Kan et al., 2013). Finally, hearing words in the presence of background noise, which exacerbates lexical competition effects on effortful listening (Kuchinsky et al., 2013), also engages control mechanisms that are associated with better speech recognition performance (Vaden et al., 2013). Indeed, cingulo-opercular and frontoparietal attention-control networks are commonly upregulated when listening to degraded auditory signals (Peelle, 2018). Together, these findings suggest a shared process dedicated to resolving both perceptual and verbal conflict, and that domain-general functions mediate conflict-adaptation phenomena. The results of the current experiment extend these findings by demonstrating that this domain-general function plays a causal role in revising misinterpretations of sentence meaning.

However, the perceptually ambiguous stimuli are harder than perceptually unambiguous ones. It is conceivable then that greater effort facilitated listeners' revision through increases in attention demands. We address this in Experiment 4. If the results of Experiment 3 can be attributed to changes in attention, then when we manipulate perceptual difficulty but remove the ambiguity (conflict) on the prior trial, the carry over effects should replicate under conditions of increased attention. If, on the other hand, the results of Experiment 3 are due to conflict-driven cognitive control, then carry over should be limited.

Experiment 4

In Experiment 3, the addition of visual noise created ambiguity that influenced language comprehension via cross-task adjustments in control. However, visual degradation alone should not engage control and affect syntactic revision if the signal itself fails to produce conflict between representations. In other words, if external cues prevent such conflict (akin to adding the cue "that's" in syntactically unambiguous sentences), then cognitive control should be unnecessary and smaller effects on sentence performance are expected on a subsequent trial. This should be so even if the visual-degradation task on the prior trial requires greater attention to see the stimuli in noise compared to when there is no noise. If the results of Experiment 3 are due to cognitive-control processes initiated by the ambiguity of the arrowheads' direction – not simply because the hard-to-see stimuli compelled more effort – then the effects should not replicate when an exogenous cue unambiguously determines the arrows' direction. The current experiment tests whether providing a visual cue to the arrows' direction, despite visual masking, fails to result in cross-task adaptation.

Method

Participants

Twenty-six right-handed adults (7 men, 19 women; mean age = 20.3 years, range = 18–22 years) who did not participate in the other three experiments were paid $10 per hour. All participants were healthy, native monolingual speakers of English, were not taking any psychoactive medications, had no history of neurological disorders, had normal or corrected-to-normal vision, and were not colour blind. They provided written informed consent, and the human participants review board at the University of Maryland approved all experimental procedures.

Materials and procedure

Experiment 4 was methodologically identical to Experiment 3 except that we modified the perception task on trial *n*-1 by providing an orientation cue to remove the ambiguity.

Perceptually easy/difficult task. Participants used the mouse buttons to indicate whether a display of five arrows (same number as in the previous tasks; see Figure 2B) located in the centre of the computer screen faced right or up. That is, the arrows never pointed left. This small change provided an additional orientation cue to participants: they never had to identify the arrowheads themselves, because a horizontal line unambiguously signalled a rightward arrow, and a vertical line unambiguously signalled an upward arrow (even if they couldn't see the arrowheads per se). Accordingly, this cue should eliminate underdetermined perceptual conflict *despite the visual mask* since direction was never ambiguous (unlike in Experiment 3, where all arrows pointed left or right and were therefore horizontal). Perceptually-difficult trials contained the same visual mask applied in Experiment 3; perceptually-easy trials had no such mask. Participants practiced a block of 96 trials (perceptually-easy and perceptually-difficult items in equal proportion) at the beginning of the session before starting the main experiment.

Results

Perceptually easy/difficult manipulation check

We analysed RTs on correct trials only (97.9% of the full dataset). As seen in Figure 3D, participants were significantly slower to respond to Perceptually Difficult (M = 484 ms, *95% CI* = [464, 504]) compared to Perceptually Easy trials (Congruent: M = 470 ms, *95% CI* = [451, 489]; $t(25) = 3.79$, $p = .001$, Cohen's $d = 0.28$). Thus, as expected, the addition of visual noise increased scene "clutter" relative to unmasked trials, thus increasing task difficulty without underdetermined conflict between the arrows' direction.

Signs of misinterpretation: syntactic ambiguity manipulation check

As can be seen in Figure 4D, participants looked more to the incorrect goal during ambiguous ($M = .16$, *95% CI* = [.14, .18]) compared to unambiguous sentences ($M = .11$, *95% CI* = [.10, .12]; $\chi^2(1, N = 26) = 8.84$, $p = .003$, estimated effect of −3.9%, standardised effect size of 0.12). Again, this shows that listeners initially misinterpreted the early arrival of "on the binder" as a goal, and would eventually have to revise.

Effect of perceptual difficulty on off-line revision (mouse-actions)

Listeners were nominally more accurate on unambiguous ($M = .97$, *95% CI* = [.95, .99]) compared to ambiguous sentences ($M = .93$, *95% CI* = [.90, .96]); $\chi^2(1, N = 26) = 3.20$, $p = .07$, estimated effect of +3.7%, standardised effect size of 0.17). Crucially however, unlike Experiments 1 and 3, the prior trial type that manipulated perceptual difficulty did not modulate this pattern (see Figure 5D); there was no Previous × Current Trial-Type Interaction ($\chi^2(1, N = 26) = 3.39$), $p > .07$, estimated effect of +7.4%, standardised effect size of 0.34

Effect of perceptual difficulty on on-line revision (eye movements)

We analysed eye movements in exactly the same way as the first three experiments, as once again fixation patterns over time were extremely similar. Figure 7D plots the proportion of looks to the correct goal in the 800-ms time window following the offset of the correct-goal word (e.g. "scarf"). As can be seen, listeners did not look more to the correct goal in this interval when ambiguous sentences followed perceptually difficult trials, compared to perceptually easy trials. Fixations on the correct goal during unambiguous sentences also appeared to be uninfluenced by prior trial type. Indeed, unlike Experiments 1 and 3, we did not find a significant Previous × Current Trial-Type Interaction ($\chi^2(1, N = 26) = 1.91$, $p = .17$, estimated effect of +8.2%, standardised effect size of 0.17). When accounting for only correct mouse-action trials, the interaction was still absent ($\chi^2(1, N = 26) = 1.49$, $p = .22$, estimated effect of +7.0%, standardised effect size of 0.15). Thus, perceptual difficulty, short of competing cues to direction on trial n-1, did not influence online syntactic revision on trial n.

Discussion of Experiment 4

We hypothesised that visual degradation that does not generate conflicting representations should not engage control and affect sentence reinterpretation, even if the degradation creates some perceptual difficulty. The goal was to further corroborate the hypothesis that online revision is driven by the detection of conflict itself and ensuing adjustments in control, more than a simple increase in task difficulty that may require increased attention. To this end, we manipulated visual attention as in Experiment 3, by retaining the perceptual mask on difficult trials and removing it on easy ones, but we modified the task by providing a cue that should eliminate any ambiguity in arrow direction. Consistent with our expectations, even though the mask made those arrows harder to see (i.e. difficulty manipulation succeeded), the lack of direction-conflict (left vs. right, as in Experiment 3) did not result in cognitive-control engagement that carried over to affect sentence revision. On-line measures revealed that listeners' looks to the correct goal in the 800-ms interval following "scarf"-offset were not impacted by prior perceptual difficulty. This suggests that the patterns in Experiment 3 cannot simply be ascribed to "greater focus" following perceptually hard trials.

But could the lack of effect in Exp. 4 be explained as a decrease in task difficulty in the degraded conditions as compared to Exp. 3? Judging by the RT values, this is highly unlikely: mean RT to perceptual conflict trials (Exp. 3) is 479 ms; mean RT to perceptually difficult trials (Exp. 4) is 484 ms. This 5-ms increase is a small difference, and the direction is inconsistent with an enhanced difficulty account of the Exp. 3 findings, and are more aligned instead with the conflict-control explanation.

Cross-experiment comparisons

One way to evaluate the extent to which the engagement of cognitive control drives sentence revision to a greater degree than focused attention is to test for cross-experiment differences. Our *a priori* hypothesis has been that discovering a misinterpretation of sentence meaning engages conflict-resolution and cognitive-control processes specifically to enable revision, more so than maintaining attention across a trial more broadly. Thus, we predicted that the conflict manipulations in Experiments 1 and 3 (which engaged cognitive control) should influence syntactic revision, but the task difficulty manipulations in Experiments 2 and 4 (which did not engage cognitive control, due to a lack of representational conflict) should not be sufficient. The statistical effects in Experiments 1 and 3 then are predicted to be significantly different from those in Experiments 2 and 4.

To test this, we looked for a three-way interaction between Experiment, Previous Trial Type, and Current

Trial Type. In separate analyses, we modelled (a) mouse-action accuracy (offline interpretations) and (b) fixations on the correct goal in the 800-ms window following the offset of the correct-goal word (e.g. "scarf"). We coded Experiment as a factor by binarizing the four experiments: we assigned a value of 1 to Experiments 1 and 3 (where we predicted conflict adaptation effects), and a value of 0 to Experiments 2 and 4 (the reference level, where we predicted no conflict adaptation). We then included Experiment as a factor and tested for the three-way interaction.

For off-line mouse-actions, we found a significant three-way interaction, indicating that Experiment interacted with the Previous Trial-Type and Current Trial-Type factors ($\chi^2 = 10.90$, $p = .01$, estimated effect of −4.6%, standardised effect size of 0.20). In other words, as hypothesised, cognitive-control engagement in Experiments 1 and 3 increased accuracy of listeners' final interpretations to a greater extent as compared to the other types of cognitive engagement in Experiments 2 and 4 (compare Figure 5A and C to Figure 5B and D). Similarly, for on-line eye-movements to the correct goal, we found a three-way interaction (($\chi^2 = 7.73$), $p = .05$, estimated effect of −6.1%, standardised effect size of 0.13). This means that cognitive-control engagement in Experiments 1 and 3 affected the time-course of listeners' revision differently than the other types of cognitive engagement in Experiments 2 and 4.

General discussion

Summary of main findings

Across four experiments, we investigated the extent to which dynamic engagement of cognitive control influenced listeners' ability to recover from misinterpretation of spoken language, and whether this effect can be discriminated from alternative explanations like difficulty associated with maintaining attention across a trial (i.e. general task engagement related to effort). A defining property of cognitive control is that it helps *recharacterize* or *adjudicate* information when confronted with *internal* conflict – arguably a cardinal demand that arises upon discovering a misanalysis of sentence meaning (Fedorenko, 2014; Novick et al., 2014, 2005; Ye & Zhou, 2009). Specifically, when cues that arrive early in an utterance are used to guide interpretation decisions (e.g. biases associated with the verb "Put"), cognitive-control procedures must take effect during real-time comprehension when other evidential cues ultimately clash with initial characterisations of the input. This creates revision pressures that must be mitigated; otherwise, communication would fail. A key prediction of our study then was that cognitive-control engagement, more so than other types of cognitive engagement, should facilitate syntactic revision. A second key prediction was that the cognitive-control system that enables revision is domain-general, operating systematically to resolve conflict regardless of whether it stems from verbal or nonverbal representations.[1]

To address these issues, our approach diverged necessarily from traditional correlational methods. Though such methods (e.g. examinations of individual differences, overlapping neural activity, co-impairments in patients) have been critical in establishing a connection between cognitive control and language processing, they do not provide insight into the nature of this connection when listeners are interpreting spoken language as it unfolds *in real time*. Critically, if cognitive control is a causal factor in listeners' ability to avoid misinterpretations, then its dynamic engagement should impact their ability to revise moment by moment. Our goal therefore was to uncover a more direct connection between cognitive control and real-time language processing by adopting an approach that could spell out the delicate procedures underlying recovery from syntactic misanalysis. To this end, we manipulated the relative engagement of cognitive control from a nonverbal source (e.g. the arrow Flanker task) in two experiments to test for both domain-generality and temporal interdependence between its deployment and successful sentence revision. In two other experiments, we manipulated different types of cognitive engagement (e.g. attention across a trial) to pinpoint the specificity of cognitive-control effects on syntactic parsing.

As predicted, when we manipulated task conditions to engage cognitive control just prior to hearing a sentence that was temporarily misunderstood, we observed fewer comprehension errors, reflecting more accurate revision. Moreover, eye-movement patterns revealed that listeners reached the revised interpretation earlier when cognitive control was relatively more engaged by the detection of conflict on an immediately preceding trial. These findings provide support for a causal interplay between conflict detection and adjustments in control that assists listeners' correction of language-processing errors – consistent with classic conflict-adaptation findings. Crucially, these effects replicated across two independent experiments that engaged cognitive control in profoundly different ways. In Experiment 1, conflict between representations of an arrow's direction – owing to interference from flanking stimuli – subsequently influenced syntactic revision. In Experiment 3, the lack of a clear bottom-up signal as to the arrowheads' direction – due to the addition of visual noise –

created underdetermined conflict (ambiguous percept) that also expedited sentence revision. These observations replicate earlier cross-task adaptation research demonstrating that detecting Stroop-conflict (a verbal task) influenced recovery from misinterpretation (Hsu & Novick, 2016; see also Thothathiri et al., 2018). Importantly, the current findings extend those results to indicate domain-general effects of cognitive-control engagement on sentence reanalysis. Even though representations of arrow stimuli are drastically different from those built during sentence comprehension, when those representations give rise to conflict, it triggers the same cognitive-control mechanism that in turn affects language processing.

But is it cognitive control? Or could these effects be ascribed to other cognitive systems that engage under harder task conditions (for reviews see Mattys et al., 2012; Peelle, 2018)? Indeed, Hussey et al. (2015) found that left prefrontal tDCS can, at least in some conditions, facilitate processes related to both cognitive control and general task difficulty during sentence processing. A major aim of this study was to isolate a process-specific mechanism that (at least partially) handles revision procedures that extend beyond the attribution of greater attentional effort under difficult task conditions. In the speech comprehension literature, effort has been defined as the "deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a [listening] task" (Pichora-Fuller et al., 2016, p. 10S). This definition highlights the variety of sensory and cognitive processes that contribute to effort, which may arise from internal (e.g. competing representations) and external (e.g. ambiguous percepts) sources (Strauss & Francis, 2017). Like neural activity within the multiple demand network (Fedorenko et al., 2013), mental effort appears to increase with many different types of task difficulty, including with the engagement of cognitive control in non-linguistic tasks (van der Wel & van Steenbergen, 2018), within speech processing tasks that involve performance monitoring, perceptual ambiguity and response competition (Kuchinsky et al., 2013), and the maintenance of vigilant attention (Kuchinsky et al., 2016). These findings demonstrate the challenge of teasing apart the component processes that are engaged in difficult task processing and thus identifying those that are critical to conflict resolution.

To address this issue, we manipulated prolonged attention to arrows that might "flip" at unpredictable times in Experiment 2, while holding constant other experimental variables that were present in Experiment 1. Crucially, in both the offline and online data, increased attention across the trial did not reliably influence the ease with which listeners revised misinterpretations. Similarly, in Experiment 4, the presence of a discernable orientation cue as to the arrows' direction meant that, unlike in Experiment 3, the identities of the stimuli were no longer "underdetermined". This small change avoided conflict between direction representations, even though arrows in noise were harder to see than arrows that were perceptually intact. Yet, the focused attention that was required to perceive the stimuli did not carry over to impact sentence revision in the same way as in Experiment 3, when the reduced signal specifically created representational conflict. Alongside the effects in Experiments 1 and 3 then, we suggest that one factor enabling listeners to overcome errors in interpretation are the linked processes of conflict detection (between incompatible representations) and ensuing adjustments in control (that resolves said conflict). We are currently adapting the series of studies reported here to manipulate conflict and effort within participants: We expect such follow-ups to demonstrate that fluctuations in cognitive control will impact revision processes for conflict sentences whereas fluctuations in attention will not. Furthermore, future studies may employ neural or physiological measures of autonomic system activity (e.g. average pupil dilation) that have been observed to index task-engagement (Kuchinsky et al., 2016) as a means to further validate our attentional demand manipulations.

Although our cross-experiment analyses indicated statistically reliable differences between Experiments 1 and 3 (cognitive control) versus Experiments 2 and 4 (attentionally demanding, perceptual difficulty), informal observations suggest that the data trends sometimes appear similar. This may be due to obvious contributions that effort makes to language comprehension. Specifically, executive functions may impact interpretation processes in at least two distinct ways: through cognitive control and attention control. As we have argued here, cognitive control regulates thoughts and actions when the intended characterisation of the input conflicts with a more dominant one (e.g. revising misinterpretations). Attention control may regulate the *collection* of information from the environment by selectively biasing perceptual processing toward a single channel. For instance, attention control may help listeners extract the intended signal by guiding perceptual processing to favour linguistic input over other sources of noise. Indeed, upregulated attention control has been shown to support finer encoding of degraded speech stimuli (Vaden et al., 2013). It is possible that any (nonsignificant) patterns resembling effects of non-conflict driven attention seen here may reflect such procedures; while these procedures are sufficient to *gather* the input (e.g. increase perceptual gain), they may simply be insufficient to *recharacterize* the input (which requires cognitive control).

Because we did not focus our inquiries on the positive effects of attention control on language comprehension, or its interactions with cognitive control, this is an empirical issue that should be investigated in future research. We predict that, whereas cognitive control acts transiently on internal (endogenous) representations as conflict resolution is required, attention control will act on perceptual processes, biasing the collection of exogenous input over sustained periods of time. Disentangling unique contributions of cognitive control and attention control is important because theories of language comprehension generally treat them as interchangeable processes. In fact, emerging findings indicate that these two sorts of executive functions, while related, may be served by distinct neural mechanisms and thus may contribute different functions during comprehension (e.g. Boudewyn & Carter, 2018b; Rommers et al., 2017). For instance, when listeners hear stories and are probed periodically for whether they were paying attention, greater mind-wandering reports correlate with lower accuracy on subsequent comprehension questions. That is, greater attention to information at the time of a probe corresponds to greater collection of and later memory for that information. Moreover, EEG data show that decreased attention is associated with increased neural oscillations in the alpha band (8–12 Hz) and more comprehension errors afterwards. While alpha power is used as an index of attentional engagement, theta power (3–8 Hz) is involved in conflict-monitoring functions (Boudewyn & Carter, 2018a; Cavanagh & Frank, 2014). Together, this suggests that, during language processing, attention control helps collect information from the exogenous signal and enables greater maintenance of that information over time. While not tested explicitly, this is consistent with our hypotheses about distinctive contributions of cognitive control and attention control to language comprehension.

Connection to previous work

While prior correlational research has been instrumental in establishing a connection between cognitive control and language processing, the findings have been mixed regarding the extent to which sentence reinterpretation is supported by a domain-general system. For instance, some results have indicated an association between revision and nonverbal cognitive control abilities (e.g. Woodard et al., 2016), suggesting domain-generality (see also Ye & Zhou, 2009), whereas others have hewn to more moderate, domain-specific conclusions: while verbal cognitive-control performance predicted syntactic revision, non-verbal performance did not (Vuong & Martin, 2011).

Discrepant patterns of results may arise for various reasons, and interpreting null correlational effects is notably problematic. And in fact, research on executive function often reports fragile correlations even among tasks that tap a *common* latent construct (e.g. inhibition; see Friedman & Miyake, 2004; Unsworth, 2010). In other words, interpreting such null correlations might lead one to conclude that canonical tasks of inhibition are unrelated to each other (despite the clear latent construct); but that would be unwarranted. By the same logic, null findings may also not reject domain-general conclusions and should not be construed as support for domain-specificity, since this interpretation is hard to reconcile alongside consistent cross-task co-localization within the LIFG during fMRI studies (for a lengthier discussion, see Hsu et al., 2017). Rather, correlations may not arise simply because some task-specific representations are not susceptible to the same level of conflict as others.

Consequently, the disparity in domain-general versus domain-specific effects may partly reflect limitations of predominant correlational methods for understanding interactions between cognitive control and language processing. For instance, correlations generally average over multiple items or test trait patterns of individual differences across participants (i.e. long-term relationships). While earlier findings imply clear links between cognitive control and parsing, how to interpret such effects is intrinsically underspecified. That is, good cognitive control may benefit syntactic revision, and poor cognitive control may harm it – but it could also be the other way around (where language skills affect cognitive control). Correlations could also manifest hidden factors that are confounded with the language and cognitive-control variables under consideration. Clarifying these cross-domain procedures thus requires methods that directly manipulate dynamic cognitive-control engagement (versus other types of cognitive engagement) during comprehension to test its immediate (i.e. moment-to-moment, not long-term) effects on subsequent interpretation, as we have done here. Additionally, multilevel-model analyses demonstrate the extent to which patterns hold simultaneously within individual participants and within individual items. This approach distinctly reveals that detecting conflict – regardless of its source – mobilises cognitive-control procedures that impact syntactic revision. Thus, we believe that conflict resolution is a domain-general process that systematically operates over domain-specific representations, be they syntactic or visual in nature (like arrows).

One key takeaway from our approach is that defining someone as having *either* good *or* bad cognitive traits (e.g. attention, cognitive control), as prior work tends to do, is likely a gross oversimplification of how people differ in these ways; and adhering to such a strict dichotomy (as individual differences studies often do) may miss conceptual nuances and perhaps generate empirical mistakes. Here, our goal was to investigate how people compare *with themselves*, under different states of cognitive engagement, to observe the real-time consequences of these subtle manipulations on language processing performance independently of the individual levels of cognitive-control ability within each of our participants. This deviates from individual differences approaches in which "executive function" measures are taken as a snapshot in time of a person's performance. A weakness of that approach, we believe, is that it typically does not account for the fact that the status of one's cognitive engagement (attention, cognitive control) naturally oscillates over the course of a day, or even throughout a short-term activity (e.g. reading, listening to the news), which suggests that such abilities are not necessarily fixed or static. Such fluctuations can influence in-the-moment performance (e.g. how much information an individual has collected and retained, and how he or she characterises that information). Studies that focus exclusively on whether a person with strong cognitive control performs differently than a person with weak cognitive control (a trait contrast) on some other task capture only a snapshot of individuals' performance in time, missing important data about how natural fluctuations in one's attention or cognitive control over the course of seconds impacts behaviour.

Moreover, tasks like Flanker, Stroop, et cetera, which are commonly used in the literature, are typically employed to assess cognitive control abilities (that is, traits). But where we diverge from prior research is that we are using the tasks to manipulate the states of cognitive engagement in real time, rather than as psychometric tests that purport to measure cognitive control as a stable trait. This is notoriously problematic because the tasks have poor internal validity, and the original forms of Stroop and Flanker were never designed as psychological tests of cognitive ability (e.g. Miyake & Friedman, 2012). We circumvent the problem in our approach because we are not administering the task to measure anything stable about a participant. Rather, we use Flanker to vary the engagement status of control procedures, prior to sentence processing, to observe the effects of this manipulation on comprehension. Such "in-the-moment" approaches, via neurostimulation or functional-adaptation paradigms (like the current work) offer distinct information than snapshot tests of cognitive traits, in which researchers capture one's behaviour at only a particular moment without (typically) acknowledging what cognitive state the participant may be in. One area that future research could pursue is to test a relationship between state and trait activity. For example, it would be of interest to investigate whether those with high trait cognitive control are better able to regulate their engagement status "in the moment," or whether those with low trait cognitive control could experience more "gain of function" through a dynamic engagement status.

Implications of current findings (with caveats)

The current series of experiments has both theoretical and applied implications. Our inference that the process that handles sentence revision is domain-general informs long-standing debates about modularity (e.g. Fodor, 1983), particularly the extent to which linguistic processes are functionally separate from nonlinguistic ones (Fedorenko et al., 2011). Our approach reveals that cognitive-control procedures, even if initiated by a nonlinguistic source, can rapidly penetrate the language-processing system. This may open the door to practical applications of this approach that include increasing the development of training paradigms to remediate comorbid deficits in cognitive control and language (e.g. Hussey et al., 2017; Novick et al., 2014).

Indeed, the patterns observed here may carry important implications for groups whose language-processing deficits stem from cognitive-control impairments (e.g. LIFG patients' failure to revise; Novick et al., 2009; Vuong & Martin, 2014). For example, the manipulation of prior trial type reveals that cognitive control drives the ability to recover from misinterpretation in real time (see also Hsu & Novick, 2016). Interestingly, when cognitive control is relatively disengaged (e.g. when prior Flanker trial is congruent), healthy adults actually begin to resemble LIFG patients: they, too, fail to revise with consistent frequency. But such failure abates when cognitive control is experimentally induced (e.g. when prior Flanker trial is incongruent). This suggests that healthy adults' occasional failure to recover from misinterpretation under normal circumstances (Christianson et al., 2006; Novick et al., 2008; Slattery et al., 2013) may be due partly to continuous fluctuations in cognitive-control *states*, which has dynamic effects on performance (Cavanagh et al., 2009). Moreover, a central observation is that revision is reliably more effective if cognitive control has been recruited. The question is whether the same causal element is present in neuropsychological groups, and whether the engagement of cognitive control has a positive impact on patients' revision as well. It may even be feasible that cognitive-control training over the long-term would remediate their difficulty revising language-processing errors, much like it does in healthy adults (e.g. Hussey et al., 2017; Novick et al., 2014).

However, there are important caveats to consider before leveraging cause-and-effect observations in the lab toward applied outcomes. Though our results show that more cognitive control results in dynamically better revision in neurologically intact adults – which is consistent with prior positive correlations (more cognitive control predicts more revision) – it is not yet clear that the same pattern would hold in special populations. For instance, in the cognitive-control literature, conflict adaptation in adults is well documented (e.g. Botvinick et al., 2001; Duthoo et al., 2014; Gratton et al., 1992). Yet patients' language comprehension may not be influenced to the same degree if their cognitive-control deficit does not arise from an inability to regulate *states* of engagement. This is an empirical issue for future research to address.

In children, cognitive-control engagement can have variable consequences. Similar to adults, 5- to 9-year-olds demonstrate conflict adaptation in Stroop (Ambrosi et al., 2016; Larson et al., 2012), Flanker (Cragg, 2016), and Simon tasks (Ambrosi et al., 2016; Iani et al., 2014). That is, they show better performance on incongruent trials that follow other incongruent trials as opposed to congruent ones (e.g. they are better at disregarding dominant but task-irrelevant cues like word form in favour of task-relevant ones, like ink colour). But unlike adults, they also sometimes show *poorer* performance – a behavioural *cost* – on incongruent trials that follow other incongruent trials as opposed to congruent ones (Karbach & Kray, 2009; Kray et al., 2012; Waxer & Morton, 2011). This may not reflect a failure in cognitive control per se, but rather a tendency for cognitive-control engagement to promote reliance on the most probabilistically reliable cues in populations with limited experience (e.g. those who are still learning), even if those cues are currently misleading. Regardless, evidence of both benefits and "costs" illustrate that the effects of dynamic cognitive-control engagement may not be fixed but rather adaptive, in service of increasing the likelihood of the most optimal performance (i.e. fewest errors). Indeed, emerging research shows that children's cognitive-control engagement may operate over cue reliability during sentence processing, i.e. the extent to which a cue predicts a particular meaning (Ovans et al., 2018).

Clearly, what cues are reliable will differ across populations, will depend on specific task properties, and will vary by environmental factors (e.g. verb biases presumably vary across populations with different language experience). While we are unaware of any conflict adaptation studies in LIFG patients, the effects of their dynamic cognitive-control engagement on syntactic revision may result in behaviours that differ from what we observe here. Healthy older adults also exhibit atrophy in prefrontal cortices, declines in cognitive-control function, and exert greater mental effort to achieve the same level of performance as younger adults (e.g. Eckert et al., 2008; Wingfield & Grossman, 2006). Minimally, these groups should be the focus of future research that tests for causal effects of cognitive-control engagement on their ability to revise. Such a programme could pave the way for understanding the effects of cognitive control states, which groups' states are more susceptible to fluctuation, and how a variable environment places different pressures on the cognitive-control system.

Before closing, we note that some accounts of conflict adaptation ascribe the results to learning contingencies between stimulus features across trials rather than dynamic engagement of conflict-control procedures per se (Schmidt & De Houwer, 2011). Critically, those critiques are focused exclusively on within-task effects (e.g. Stroop-to-Stroop; Flanker-to-Flanker; etc.) where trial repetitions and contingency learning confounds are frequently present. In deploying the functional-adaptation paradigm here, we took special care to avoid such confounds in our designs. Indeed, demonstration of the *cross-task* effects reported here are difficult to explain on such an account (Hsu & Novick, 2016), and several studies show that the adaptation effects remain with a confound-minimized approach (e.g. Erb & Aschenbrenner, 2019; Duthoo et al., 2014; Larson et al., 2016). Others who show within-task adaptation effects but fail to observe cross-task effects attribute this pattern to a process of binding domain-specific representations to domain-general control regions, which is subject to incremental learning (Akçay & Hazeltine, 2011; Freund & Nozari, 2018). Others find that the expression of cross-task adjustments in control depends on whether participants represent the two distinct tasks as one instead of two (Grant et al., 2020). Despite our consistent cross-task effects in this paper and elsewhere (Adler et al., 2019; Hsu & Novick, 2016; Kan et al., 2013; Thothathiri et al., 2018), it is conceivable that future work on language comprehension will fail to find such evidence, in which case we will re-evaluate our hypotheses within a learning or task-set-maintenance account. Such an adjustment in our theoretical position however would not necessarily invalidate other aspects of our hypotheses concerning the distinctive contributions of cognitive control and effort. In the meantime, while some research shows that cognitive control in one task does not always confer better control in another (e.g. Akçay & Hazeltine, 2011; Egner et al., 2007; Freund & Nozari, 2018), our data suggest an intricate role that cognitive-control procedures may play to help ensure that comprehension stays on track: its relative engagement facilitates sentence-revision processes as linguistic input is still unfolding.

Final comments

The present work aimed to understand how engagement of cognitive control is a pivotal factor in listeners' ability to revise misinterpretations of language input in real time. Minimal changes in experimental stimuli allowed us to isolate the relative contribution of conflict-driven cognitive control processes from task engagement (e.g. prolonged attention) processes to both offline and online measures of sentence parsing. These results expand upon previous research by revealing a tight link specifically between conflict detection and revision processes during sentence comprehension. Importantly, this cognitive control carryover stemmed from a nonverbal task, suggesting that sentence revision is supported by domain-general cognitive functions. We conclude that listeners' ability to override an early structural analysis, in view of late-arriving conflicting evidence, is driven by the dynamic engagement of cognitive-control procedures in real time.

Note

1. Although our focus in the current paper is on syntactic ambiguity, we do not intend to suggest that cognitive control is needed for *only* revision procedures, or when there is processing difficulty. Future research should consider ways in which cognitive control is engaged in a causal way under other language processing conditions at different levels of representation, and to what degree it is (e.g. how cognitive control influences communicative success during joint action and social exchanges).

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