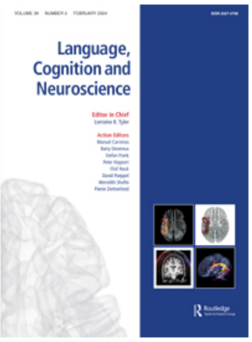

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Linking cognitive control to language comprehension: proportion congruency effects in syntactic ambiguity resolution

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ABSTRACT

Two experiments investigated the effect of sustained cognitive control engagement on syntactic ambiguity resolution. Participants heard (Experiment 1) or read (Experiment 2) garden path sentences like "Put the kiwi on the rectangle on the circle", in which "on the rectangle" could temporarily reflect either a destination of "Put" or modifier of "kiwi", and they viewed visual arrays with a kiwi on a rectangle and an empty rectangle and circle. Cognitive control was manipulated experimentally by interleaving sentence trials among either mostly incongruent or mostly congruent Stroop trials. Across both experiments, garden path mouse cursor movements to incorrect destinations were reduced when sentence trials were interleaved among mostly incongruent Stroop trials, and in Experiment 2, garden path reading time effects were also reduced in this condition. These results suggest that a high proportion of incongruent trials supports the sustained engagement of cognitive control and causally improves sentence comprehension across (i.e. spoken and written) modalities.

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Cognitive control; executive functions; language comprehension; mouse cursor tracking; syntactic ambiguity resolution

Ambiguity is pervasive in language. For example, Groucho Marx's joke, "One morning I shot an elephant in my pajamas. How he got into my pajamas, I'll never know", plays on the syntactic ambiguity of "in my pajamas". What mechanisms support incremental language processing and ambiguity resolution? The aim of the current research was to investigate the effect of sustained cognitive control engagement across both spoken language and reading comprehension.

Over a half century (e.g. Bever, 1970), garden path sentences have provided an essential tool for probing the mechanisms that support sentence comprehension. Garden path sentences, like Bever's (1970) "The horse raced past the barn fell", include temporary syntactic ambiguities that participants typically misinterpret. Garden path sentences have provided important insights into the incrementality of sentence comprehension and the revision of misinterpretations. For example, participants typically (mis)interpret "raced" as a main verb (i.e. with "horse" as its subject) and they must revise this incremental (mis)interpretation at "fell" (i.e. as a reduced relative to yield a grammatical parse). Participants often fail to parse (i.e. revise) severe garden path sentences like Bever's (1970) altogether, and even in milder cases (e.g. "The defendant examined by the lawyer turned out to be unreliable"; Ferreira & Clifton, 1986), their processing is typically disrupted at disambiguation (e.g. "by").

The mechanisms that support syntactic ambiguity resolution are still under debate. Central to the current investigation, Novick and colleagues (e.g. Novick et al., 2005) emphasise the link between sentence comprehension and cognitive control. Cognitive control refers to participants' ability to regulate their thoughts and actions towards an internal goal that works by flexibly and effectively biasing attention towards information that is task relevant rather than irrelevant (e.g. Botvinick et al., 2001; Miller & Cohen, 2001). Cognitive control is hypothesised to allow participants to inhibit incorrect information (e.g. representations, schemas, prepotent responses, etc.) and use newly reinterpreted information to make appropriate responses. January et al. (2009; see also of Hsu et al., 2017) found that overlapping brain

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regions (e.g. left inferior frontal gyrus) were activated within individual participants when they engaged either in tasks linked to cognitive control or processed syntactic conflicts, suggesting a potential link between the two. Their participants heard syntactically ambiguous sentences like "Clean the pig with the leaf", which has both an instrument (e.g. clean the pig using …) and modifier (e.g. clean the pig that has …) interpretation. These findings suggest that participants recruited (e.g. brain regions associated with) cognitive control to resolve the conflict between these interpretations.

Compellingly, Hsu and Novick (2016) provide evidence for a causal link between cognitive control and sentence comprehension. They found that dynamically manipulating cognitive control through the Stroop (1935) task facilitated the processing of garden path sentences. In the classic Stroop task, participants are presented colour words in congruent (e.g. the word "blue" presented in blue) or incongruent (e.g. the word "orange" presented in blue) colours, and they are tasked with ignoring the meaning of each word and instead identifying the colour it is presented in. Slower responses and more errors are typically observed for incongruent than congruent stimuli. Hsu and Novick's (2016) manipulation is rooted in conflict adaptation, which reflects participants' better (e.g. Stroop) performance immediately after an incongruent than congruent trial (e.g. Gratton et al., 1992). This effect, which is often referred to as a congruency sequence effect or Gratton effect, is attributed to the persistent engagement of cognitive control immediately after experiencing an incongruent trial (e.g. Botvinick et al., 2001; Egner, 2008). The experience of conflict encountered on an incongruent trial is hypothesised to subsequently engage cognitive control, which biases attention away from irrelevant (e.g. the meaning of a word like "blue") and towards relevant (e.g. the colour a word like "blue" is presented in) information, and this engagement is also hypothesised to persist to subsequent trials. Moreover, Freitas et al. (2007) showed that this engagement also spans domains, providing evidence of cross-task adaptation of cognitive control (e.g. see Ness et al., 2023): they interleaved Flankers and Stroop trials and observed improvements on Flankers trials that were preceded by incongruent Stroop trials and on Stroop trials that were preceded by incongruent Flankers trials. Relatedly, Hsu and Novick's (2016) participants heard garden path sentences like "Put the frog on the napkin onto the box" while viewing visual arrays with objects like a frog on a napkin and empty napkin. Participants typically (mis)interpret "on the napkin" as the destination of "Put" and this incremental (mis)interpretation must be revised at "onto" (i.e. as a modifier of "frog" to yield a grammatical parse; see also Tanenhaus et al., 1995). When sentence trials were preceded by an incongruent Stroop trial, participants made fewer errors performing this action. Thus, engagement of cognitive control on the preceding Stroop trial facilitated sentence comprehension on the subsequent sentence trial, supporting a causal link between the two. Closely related findings have also been reported for other cognitive control tasks (e.g. Hsu et al., 2021) and sentence processing phenomena (e.g. Ovans et al., 2022; Thothathiri et al., 2018).

While a growing literature links sentence comprehension to cognitive control, this link is not without controversy. For example, in research preceding Hsu and Novick (2016), Kan et al. (2013) focused on the influence of syntactic ambiguity resolution on Stroop performance (e.g. in contrast, the influence of Stroop on sentences was the focus of Hsu & Novick, 2016). They observed improvements on Stroop trials when they were preceded by garden path as compared to control sentence trials. However, in exploratory analyses (i.e. these were not their focus), they did not observe improvements on sentence trials when they were preceded by incongruent as compared to congruent Stroop trials, which contrasts with the findings of Hsu and Novick (2016). Relatedly, Aczel et al. (2021) and Dudschig (2022) failed to replicate the influence of sentences on Stroop, contrasting with Kan et al. (2013), although Aczel et al. (2021) did observe effects on accuracy. Taken together, these findings suggest that the link between sentence comprehension and cognitive control may not be as clear and robust as perhaps implied by findings like Hsu and Novick (2016). Moreover, like Hsu and Novick (2016), Patra et al. (2023) focused on the influence of Stroop on sentences, but unlike Hsu and Novick (2016), did not observe improvements on sentence trials when they were preceded by incongruent as compared to congruent Stroop trials. On balance, this mix of findings (e.g. see also Simi et al., 2023) suggests that engaging cognitive control on a preceding Stroop trial may not clearly and robustly influence sentence comprehension.

Building on this mix of findings, the current research aimed to investigate the link between sentence comprehension and cognitive control by focusing on sustained cognitive control engagement. A range of methodologies and materials have been used in prior research, and thus a complete explanation of prior findings is outside the scope of the current research. However, central to the current investigation, Kan et al. (2013) highlight disengagement of cognitive control over time. Again, Kan et al. (2013) observed influences of sentences on Stroop, but not Stroop on sentences (e.g. see their exploratory analyses). They argue this this pattern may be explained by the time between their Stroop trials and the critical (e.g. disambiguating) words in their sentence trials, during which cognitive control may disengage. Consistent with this argument, congruency sequence effects (i.e. which focus on conflict adaptation across back-to-back trials; Gratton et al., 1992), have been shown to decay rapidly (e.g. Duthoo et al., 2014; Egner et al., 2010; see also Ness et al., 2023). Moreover, disengagement over time may be more of an issue for some methodologies and/or materials than others (e.g. perhaps reading, as highlighted in Kan et al., 2013; also see Aczel et al., 2021; Dudschig, 2022; Patra et al., 2023). To counter this disengagement, the current research focused on proportion congruency effects. In contrast to congruency sequence effects (e.g. Gratton et al., 1992), which focus on back-to-back trials, proportion congruency effects reflect participants' better (e.g. Stroop) performance (i.e. reduced RT and error rate differences between incongruent and congruent Stroop trials) when participants are presented (e.g. blocks of) mostly incongruent rather than mostly congruent trials (e.g. Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979). This effect is attributed to the proactive engagement of cognitive control when trials with conflict are more likely. Higher proportions of incongruent trials are hypothesised to engage cognitive control in a sustained manner, unlike congruency sequence effects that affect back-to-back trials, biasing attention away from irrelevant and towards relevant information across blocks of trials (e.g. Cheesman & Merikle, 1986; Lindsay & Jacoby, 1994; Lowe & Mitterer, 1982; West & Baylis, 1998).

The current research used a proportion congruency manipulation to support the sustained engagement of participants' cognitive control. Like Hsu and Novick (2016), the current research interleaved Stroop and sentence trials, although instead of having an equal number of each and presenting the Stroop and sentence trials one after another, participants mostly encountered Stroop trials, with sentence trials interspersed within them. Additionally, rather than presenting equal numbers of congruent and incongruent Stroop trials, as is typical of the literature, participants were presented either mostly incongruent or mostly congruent Stroop trials as part of the proportion congruency manipulation. Again, this proportion congruency manipulation was hypothesised to support the sustained engagement of cognitive control (e.g. Bugg, 2017; Bugg & Crump, 2012; Wühr et al., 2015). Complementing this proportion congruency manipulation, each sentence trial was also preceded by an incongruent Stroop trial in the mostly incongruent condition or congruent Stroop trial in the mostly congruent condition. Thus, cognitive control was expected to be engaged in a complementary way across both blocks of trials (i.e. via the proportion congruency manipulation) and back-to-back (i.e. Stroop-sentence) trials (e.g. see conflict adaptation; Gratton et al., 1992). It was hypothesised that the proportion congruency manipulation would sustain cognitive control engagement across the experiment and yield clear and robust improvements in performance on sentence trials interleaved among mostly incongruent rather than mostly congruent Stroop trials.

The current research used internet-mediated mouse cursor tracking to investigate the causal link between cognitive control and sentence comprehension. Alongside visual world eye tracking (e.g. Hsu & Novick, 2016; Hsu et al., 2021; Tanenhaus et al., 1995), mouse cursor tracking has also been used to investigate the incrementality of sentence comprehension and the revision of misinterpretations (e.g. Farmer et al., 2007; Farmer et al., 2007; Kukona et al., 2022). For example, Kukona et al.'s (2022) participants heard garden path sentences like "Put the kiwi on the rectangle on the circle" while viewing visual arrays with objects like a kiwi on a rectangle and an empty rectangle and circle. Their participants' mouse cursor movements were attracted to the empty rectangle (e.g. compared to unambiguous controls like "Put the kiwi that's on the rectangle on the circle"), reflecting their (mis)interpretion of "on the rectangle" as the destination of "Put" (e.g. rather than modifier of "kiwi") and paralleling prior eye movement findings. Likewise, participants in the current research were presented garden path sentences like "Put the kiwi on the rectangle on the circle" or unambiguous controls, and their mouse cursor movements were tracked while they engaged with visual arrays like Figure 1. To test for a causal link between cognitive control and sentence comprehension, sentence trials were interleaved among either mostly incongruent or mostly congruent Stroop trials. Again, to engage cognitive control in a complementary way across both blocks of trials as well as back-to-back trials, the Stroop trial immediately preceding each sentence trial was also incongruent in the mostly incongruent condition or congruent in the mostly congruent condition. Finally, to test the impact of cognitive control engagement across both spoken language and reading comprehension, participants listened to a sentence and simultaneously engaged with its visual array in Experiment 1, while participants read a sentence before engaging with its visual array in Experiment 2. If sentence comprehension is supported by cognitive control across modalities, improved performance was predicted on sentence trials interleaved among mostly incongruent rather than mostly congruent Stroop trials.

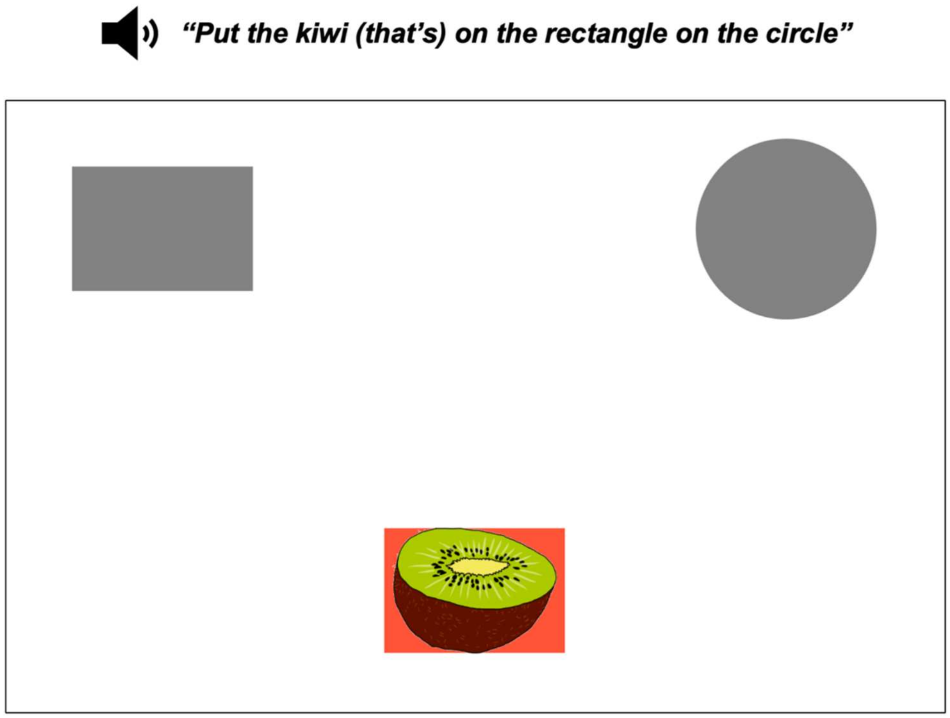

Figure 1. Example visual array and ambiguous and unambiguous (i.e. “that’s”) sentence from Experiment 1. Participants heard the sentence and used their mouse cursor to follow the instruction (i.e. clicking and draging the kiwi to the circle).

Experiment 1

Experiment 1 investigated spoken language comprehension. Alongside hearing garden path sentences, participants’ cognitive control was manipulated experimentally by interleaving sentence trials among either mostly incongruent or mostly congruent Stroop trials.

Method

Participants

Fifty-four undergraduates were recruited from De Montfort University to participate for course credit. All participants were native English speakers based in England, UK. Six participants were excluded based on their poor sentence accuracies (condition means of 50% or below). Ethical approval was obtained from the Faculty Research Ethics Committee, Faculty of Health and Life Sciences, De Montfort University (Ref: 3661). Informed consent was obtained from all participants.

Design

A 2 (Proportion Congruency: Mostly Congruent vs. Mostly Incongruent) x 2 (Sentence Ambiguity: Ambiguous vs. Unambiguous) design was used. Proportion Congruency was manipulated between participants, such that participants were randomly assigned to either the Mostly Congruent (75% congruent Stroop trials) or Mostly Incongruent (75% incongruent Stroop trials) condition, while Sentence Ambiguity was manipulated within participants, such that participants randomly heard either an Ambiguous or Unambiguous sentence on each experimental sentence trial.

Materials

The experiment was programmed in PsychoPy (Peirce et al., 2019) and internet-mediated participation was on Pavlovia (https://www.pavlovia.org). Visual displays (e.g. sizes, resolutions, etc.) varied across participants and thus visual stimuli used spatial units that were relative to the height of the display window. The centre of the display window was (0, 0) and the top and bottom of the display window were 0.5 and −0.5, respectively. In the Stroop task, participants were presented words in purple, green or blue lower case Arial font against a white background. Font height was 0.05 spatial units and words were centred at (0, 0). On congruent trials, words spelled out the colour they were presented in (i.e. “purple” in purple, “green” in green or “blue” in blue), while on incongruent trials, words spelled out different colours that were not responses (i.e. “red” in purple, “yellow” in green or “orange” in blue). Thus, semantic representations conflicted in incongruent trials (e.g. red vs. purple), paralleling sentence trials (e.g. destination vs. modifier), while responses did not (e.g. presenting "purple" in green or blue would also introduce conflict between their corresponding responses; e.g. Milham et al., 2001; Parris et al., 2022). In addition, word-colour contingencies across congruent and incongruent trials were matched, such that each congruent or incongruent word only appeared in one colour (e.g. see Hasshim & Parris, 2021).

Twenty-four experimental visual arrays were also created for sentence trials based on Kukona et al. (2022; see Figure 1). Each visual array included a brightly coloured circle, rectangle or triangle centred at the bottom, and a gray circle, rectangle or triangle in each of the corners at the top. The shapes were 0.15 × 0.15 spatial units. The brightly coloured shape at the bottom was centred at (0, −0.3) and the gray shapes at the top were centred at (±0.3, 0.3). At the beginning of each trial, an object (e.g. kiwi) was depicted located on the shape at the bottom. The shapes at the top always differed from each other (e.g. empty rectangle vs. circle), and the shape at the bottom (e.g. rectangle) was always the same as one of the shapes at the top. Each visual array was presented with a syntactically ambiguous (e.g. "Put the kiwi on the rectangle on the circle") or unambiguous (e.g. "Put the kiwi that's on the rectangle on the circle") sentence, which was recorded by a female native speaker of British English (duration $M = 3{,}221$ ms, $SD = 240$). The experimental materials are described in the supplementary materials. Twenty-four filler visual arrays were also created, which were presented with syntactically simpler sentences (e.g. "Put the bench on the rectangle").

Procedure

Participants were instructed to use either a desktop or laptop computer and either a mouse or trackpad. Participants began the experiment with two practice blocks. The first practice block familiarised participants with the Stroop task. Participants responded to 6 congruent and 6 incongruent trials in a random order. On each trial, participants were presented a black fixation cross horizontally and vertically centred against a white background for 1000 ms, which was immediately replaced with a word in a congruent or incongruent colour. The word remained on screen until a keyboard response was made. Participants were instructed to use their keyboard to respond to words in purple font with 1, green with 2 and blue with 3. Finally, feedback ("Correct!" or "Oops! That was wrong.") was provided for 1000 ms. The second practice block familiarised participants with the interleaving of Stroop and sentence trials. Stroop trials followed the same procedure as the first practice block except that feedback was not provided. In addition, after the fifth and 12th Stroop trial (i.e. of 12), a sentence trial was presented. On each sentence trial, participants were presented a black square centred on the bottom of the screen against a white background. The black square was 0.025 × 0.025 spatial units centred at (0, −0.3). Upon clicking on the black square, participants viewed the corresponding visual array (i.e. with three shapes and an object; see Figure 1). After a 1000 ms preview, participants heard a corresponding sentence. Participants were instructed to perform the action described by each sentence, using their mouse cursor to click on the object and drag it to the corresponding shape at the top of the screen. They ended each trial by using their mouse cursor to click again.

The experiment included 48 sentence trials interleaved among 192 Stroop trials. Participants were randomly assigned to either the Mostly Congruent condition, which included 144 congruent and 48 incongruent Stroop trials, or the Mostly Incongruent condition, which included 48 congruent and 144 incongruent Stroop trials. The order of the Stroop and sentence trials was randomised, with the only constraint being that sentence trials were always immediately preceded by a congruent Stroop trial in the Mostly Congruent condition, or an incongruent Stroop trial in the Mostly Incongruent condition. While Hsu and Novick (2016) manipulated cognitive control within participants by presenting either a congruent or incongruent Stroop trial before each sentence trial, the current research did so by using a between-participants list-wide proportion congruency manipulation (e.g. Bugg, 2017; Bugg & Crump, 2012; Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979), which presented either mostly congruent or mostly incongruent Stroop trials, alongside manipulating the congruency of the immediately preceding Stroop trial. Thus, participants engaged with multiple Stroop trials between successive sentence trials (i.e. an average ratio of 4:1). Participants were randomly presented either an Ambiguous or Unambiguous sentence on each of the 24 experimental sentence trials. Participants were also presented 24 filler sentence trials.

Results

First, the impact of proportion congruency on participants' Stroop performance was analysed. Mean Stroop accuracies and RTs (see Table 1) were computed by participants and submitted to mixed effect models with deviation coded fixed effects of Proportion Congruency (Mostly Congruent = −0.5; Mostly Incongruent = 0.5), Trial Congruency (Congruent = −0.5; Incongruent = 0.5) and their interaction, and random intercepts by participants. Models were run throughout in *R* using *lme4* (Bates et al., 2015) and *lmerTest* (Kuznetsova et al.,

Table 1. Experiment 1: Mean Stroop accuracies and RTs by proportion congruency and trial congruency condition.

	Accuracy (%)		RT (ms)	
	Congruent	Incongruent	Congruent	Incongruent
Mostly Congruent	97.41 (2.50)	97.99 (2.45)	687.65 (165.67)	737.48 (184.63)
Mostly Incongruent	96.69 (3.23)	98.55 (1.43)	703.58 (148.18)	702.98 (137.96)

2017). Stroop trials immediately following sentence trials (i.e. reflecting task switches) were excluded. Inaccurate Stroop trials, as well as Stroop trials with RTs below 200 ms or above 2500 ms, were also excluded from the analysis of RTs, which were log transformed. The analysis of accuracies revealed a significant effect of Trial Congruency, *Est.* = 1.22, *SE* = 0.46, $t(46) = 2.66$, $p < .05$, such that accuracies were lower in Congruent than Incongruent trials, but neither the effect of Proportion Congruency, *Est.* = −0.08, *SE* = 0.56, $t(46) = -0.15$, $p = .88$, nor their interaction, *Est.* = 1.27, *SE* = 0.92, $t(46) = 1.39$, $p = .17$, were significant. Thus, perhaps surprisingly, accuracies were significantly higher on Incongruent trials; however, accuracies were very near ceiling across all conditions, and this effect appeared to depend on a very small difference (i.e. just over 1%) in the Mostly Incongruent condition (e.g. in which engagement of cognitive control may also have improved the accuracy of Incongruent trials). In contrast, the analysis of RTs revealed a significant interaction of Proportion Congruency and Trial Congruency, *Est.* = −0.07, *SE* = 0.02, $t(46) = -3.34$, $p < .01$, such that Stroop effects were more pronounced in the Mostly Congruent than Mostly Incongruent condition. These RT results are consistent with the proportion congruency literature, suggesting that the Mostly Incongruent condition weakened the Stroop effect by engaging cognitive control.

Second, the impact of proportion congruency on participants' sentence comprehension was analysed. Sentence accuracies (e.g. as reflected in accurately moving the kiwi from the rectangle to the circle) were submitted to a mixed effect model with fixed effects of Proportion Congruency, Sentence Ambiguity (Ambiguous = −0.5; Unambiguous = 0.5) and their interaction, and random intercepts by participants and items (slopes were excluded due to issues with fit). The analysis revealed a significant effect of Sentence Ambiguity, *Est.* = 1.70, *SE* = 0.56, $z = 3.05$, $p < .01$, such that accuracies were higher for Unambiguous (Mostly Congruent $M = 99.12$, $SD = 3.44$; Mostly Incongruent $M = 99.29$, $SD = 2.27$) than Ambiguous (Mostly Congruent $M = 95.13$, $SD = 8.06$; Mostly Incongruent $M = 97.17$, $SD = 6.51$) sentences, but neither the effect of Proportion Congruency, *Est.* = 0.19, SE = 0.63, $z = 0.30$, $p = .77$, nor their interaction, *Est.* = −0.88, *SE* = 1.12, $z = -0.79$, $p = .43$, were significant.

Third, the impact of proportion congruency on participants' trajectories was analysed. Inaccurate sentence trials, as well as trials with log trajectory RTs more than 2.5 standard deviations above the global mean (2.31%), were excluded. Left/right target presentations were combined by inverting the horizontal axis in the former. Visual displays (e.g. sizes, resolutions, etc.) varied across participants and thus normalised spatial coordinates were computed for each trial relative to the start and end of each within-trial trajectory. The start was normalised as (0, 0) and the end as (1, 1). Thus, trajectory coordinates were horizontally and vertically proportional to the distance separating the start and end of each within-trial trajectory. Trajectories across the visual array were aggregated by dividing each trial into 101 normalised time slices (e.g. see Spivey et al., 2005). Mean trajectories are plotted by Proportion Congruency condition in Figure 2A and B. Mean signed deviations across time from the line connecting the start and end of each within-trial trajectory were also computed in 100 ms time slices from the onset of the modifier (e.g. "rectangle" in "Put the kiwi on the rectangle on the circle"), when garden path effects were expected to emerge. Mean deviations are plotted by Proportion Congruency condition in Figure 3A and B.

To assess time course differences in participants' trajectories, difference curves were computed by participants by subtracting the mean deviations for Unambiguous from Ambiguous sentences between modifier onset and mean sentence offset. Difference curves are plotted by Proportion Congruency condition in Figure 4A. Difference curves were submitted to a by-participants growth curve analysis (e.g. Mirman, 2017; Mirman et al., 2008) with orthogonal intercept, linear and quadratic polynomial terms, their interactions with a fixed effect of Proportion Congruency, and random slopes for each term by participants. Results are reported in Table 2 and depicted in Figure 4A. The significant effect of Proportion Congruency on the quadratic term indicates that proportion congruency impacted the curvature of participants' difference curves, as reflected in the steeper peak of the Mostly Congruent as compared to Mostly Incongruent condition (e.g. see the "on the" time window in Figure 4A).

Finally, the results of the growth curve analysis were also confirmed by a simplified analysis focused on the

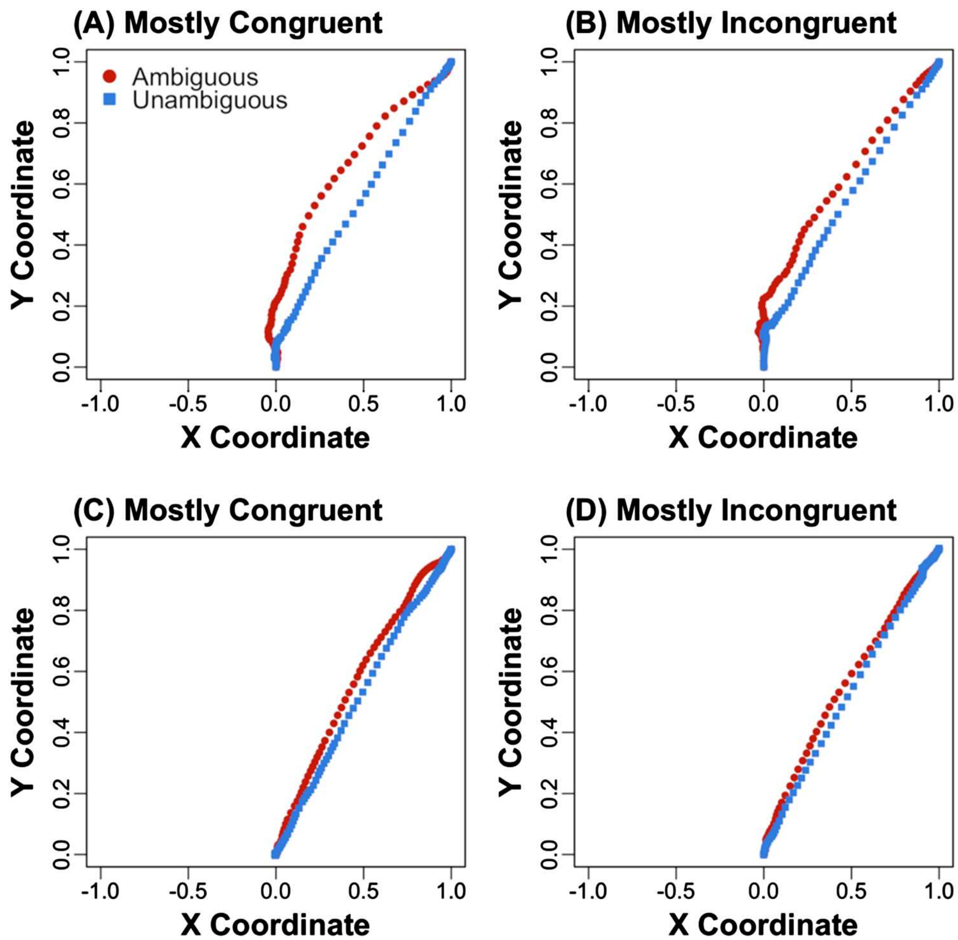

Figure 2. Time normalised mean trajectories across the visual array for ambiguous and unambiguous sentences in the mostly congruent (A, C) versus incongruent (B, D) condition in Experiments 1 (A, B) and 2 (C, D).

"on the" time window, when the difference curves diverged maximally (e.g. see Figure 4A). Within this window, maximum signed deviations (MDs) were computed for each within-trial trajectory from the line connecting its starting and ending coordinates. MDs were submitted to a mixed effect model with fixed effects of Proportion Congruency, Sentence Ambiguity and their interaction, and random intercepts by participants and items (slopes were excluded due to issues with fit). The analysis revealed a significant interaction of Proportion Congruency and Sentence Ambiguity, $Est. = 0.10$, $SE = 0.04$, $t(1056) = 2.51$, $p < .05$, such that garden path effects were more pronounced in the Mostly Congruent (Ambiguous $M = 0.27$, $SD = 0.25$; Unambiguous $M = 0.06$, $SD = 0.09$) than Mostly Incongruent (Ambiguous $M = 0.20$, $SD = 0.24$; Unambiguous $M = 0.10$, $SD = 0.16$) condition.

Discussion

Experiment 1 yielded three key results. First, Stroop RT effects were reduced in the Mostly Incongruent compared to Mostly Congruent condition. Consistent with the proportion congruency literature (Bugg, 2017; Bugg & Crump, 2012), these results suggest that a higher proportion of incongruent trials improves Stroop performance by engaging cognitive control (i.e. to bias attention toward task-relevant rather than task-irrelevant information across trials). Second, participants hearing sentences like "Put the kiwi on the rectangle on the circle" made mouse cursor movements to objects like an empty rectangle, reflecting the (mis)interpretation of "on the rectangle" (i.e. as destination). Consistent with the garden path literature (e.g. Tanenhaus et al., 1995), these results suggest that participants are led down the garden path by propositional phrase attachment ambiguities, which also impacted motor movements by the hand. Finally, these garden path effects were also reduced in the Mostly Incongruent compared to Mostly Congruent condition. When participants heard garden path sentences, their trajectories tended to deviate less to the incorrect object in the Mostly Incongruent condition compared to the Mostly Congruent

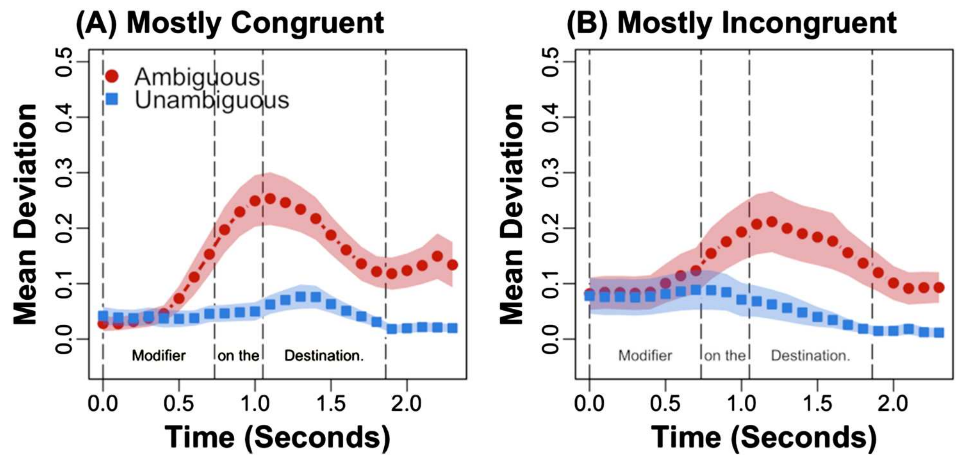

Figure 3. Experiment 1: Mean deviations from the line connecting the start and end of each within-trial trajectory for ambiguous and unambiguous sentences in the mostly congruent (A) versus incongruent (B) condition. The plots span modifier (e.g. "rectangle" in "Put the kiwi on the rectangle on the circle") onset to 500 ms following mean destination (e.g. "circle") offset. Shaded bands show SEs and vertical lines show mean modifier offset and destination onset and offset.

condition. Consistent with Hsu and Novick (2016), these results suggest that cognitive control causally supports syntactic ambiguity resolution during spoken language comprehension. Novelly, these results also extend prior research by revealing that internet-mediated mouse cursor tracking is sensitive to this link. Moreover, these results suggest that proportion congruency effects extend from the Stroop domain to spoken language comprehension.

However, typical of the literature (e.g. Hsu & Novick, 2016), Experiment 1 focused on spoken language comprehension. Thus, whether cognitive control causally supports syntactic ambiguity resolution across (i.e. spoken and written) modalities remains unclear. To the contrary, recent findings from internet-mediated reading studies (e.g. Aczel et al., 2021; Dudschig, 2022; Patra et al., 2023; Simi et al., 2023) suggest that the link between sentence comprehension and cognitive control may not be as clear and robust as perhaps observed in Experiment 1. To assess the impact of cognitive control on reading comprehension, Experiment 2 closely followed Experiment 1, but during sentence trials, participants read a sentence before engaging with its visual array.

Experiment 2

Experiment 2 closely followed Experiment 1, but reading comprehension was investigated. Alongside reading garden path sentences, participants' cognitive control was manipulated experimentally by interleaving sentence trials among either mostly incongruent or mostly congruent Stroop trials.

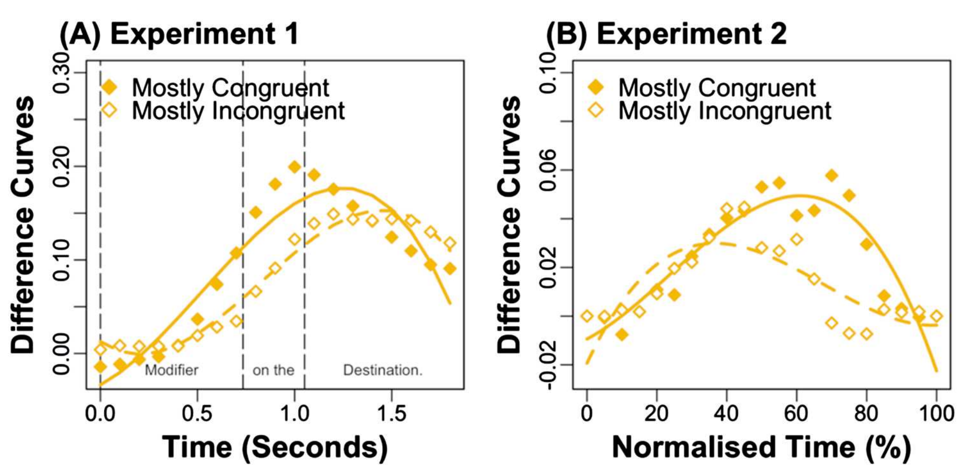

Figure 4. Difference curves (i.e. for ambiguous minus unambiguous sentences) in the mostly congruent versus incongruent condition in Experiment 1 (A) and 2 (B). Curves show model fits and symbols show means.

Table 2. Experiment 1: Growth curve analysis of the (ambiguous – unambiguous) difference curves in the mostly congruent versus mostly incongruent condition.

Fixed effect	*Est. (SE)*	*t*	*p*
Intercept	8.72 (1.35)	6.43	< .001
Linear	22.17 (4.34)	5.11	< .001
Quadratic	−11.75 (3.01)	−3.91	< .001
Cubic	−8.48 (2.20)	−3.86	< .001
Proportion	−1.59 (2.71)	−0.59	.56
Pro x Linear	2.12 (8.68)	0.24	.81
Pro x Quadratic	15.32 (6.01)	2.55	< .05
Pro x Cubic	−0.68 (4.40)	−0.16	.88

Note. *Est*. and *SE* x 10^{-2}.

Method

Participants

Fifty-four individuals were recruited through Prolific (https://www.prolific.co) to participate for payment (£7.50/hour). All participants were native English speakers from the UK. Four participants were excluded based on their poor sentence accuracies (condition means of 50% or below) and two participants were excluded based on their poor Stroop accuracies (means below 90%).

Design and materials

A 2 (Proportion Congruency: Mostly Incongruent vs Mostly Congruent) x 2 (Sentence Ambiguity: Ambiguous vs Unambiguous) design that was identical to Experiment 1, as well as the same Stroop and sentence materials, were used.

Procedure

The procedure closely followed Experiment 1, but sentence trials were modified to use a reading rather than spoken language task. In contrast to Experiment 1, participants read a written sentence first using a self-paced moving-window task, and then they engaged with its visual array second (e.g. see Figure 5). On each sentence trial, participants were presented a vertically centred and left justified written sentence. The location of the sentence-initial character was constant across sentences regardless of length. Sentences were presented in black Courier New font against a white background. Font height was 0.02 spatial units. At the beginning of each trial, each character (including punctuation) was replaced by a hashmark (#). Sentences was presented above a black square. The black square was 0.025 × 0.025 spatial units centred at (0, −0.3). Upon clicking on the black square, the first word in the sentence was unmasked; with subsequent clicks, the previously unmasked word was remasked and the next word in the sentence was simultaneously unmasked. Each word was unmasked only once, and participants could not revisit previously unmasked words. There was no time limit on how long words could be unmasked for. After unmasking the final word in the sentence, the final click on the black square removed the sentence and black square from the screen, and participants viewed the corresponding visual array (i.e. with three shapes and an object). As in Experiment 1, participants were instructed to perform the action described by each sentence. Experimental sentences were identical to Experiment 1. Filler sentences were modified (e.g. "Put the bench on the rectangle not the triangle") to make them a similar length to experimental sentences. Otherwise, the (e.g. practice) blocks and interleaved Stroop trials were identical to Experiment 1.

Results

First, the impact of proportion congruency on participants' Stroop accuracies and RTs (see Table 3) was analysed (e.g. see Experiment 1). The analysis of accuracies revealed a marginal effect of Trial Congruency, *Est.* = 0.58, *SE* = 0.31, $t(46) = 1.84$, $p = .07$, such that accuracies were marginally lower in Congruent than Incongruent trials (i.e. perhaps surprisingly again but closely following Experiment 1; however, accuracies were again very near ceiling across all conditions), but neither the effect of Proportion Congruency, *Est.* = 0.53, *SE* = 0.35, $t(46) = 1.51$, $p = .14$, nor their interaction, *Est.* = 0.01, *SE* = 0.63, $t(46) = 0.02$, $p = .99$, were significant. In contrast, the analysis of RTs revealed a significant interaction of Proportion Congruency and Trial Congruency, *Est.* = −0.08, *SE* = 0.02, $t(46) = -3.93$, $p < .001$, such that Stroop effects were more pronounced in the Mostly Congruent than Mostly Incongruent condition.

Second, the impact of proportion congruency on participants' sentence accuracies was analysed (e.g. as reflected in moving the kiwi from the rectangle to the circle; see Experiment 1). For Ambiguous and Unambiguous sentences, respectively, mean sentence accuracies were 89.96 (11.18) and 98.04 (4.10) in the Mostly Congruent condition, and 95.37 (7.53) and 99.68 (1.72) in the Mostly Incongruent condition. The analysis included random intercepts by participants and items, and random slopes for sentence ambiguity by items (slopes were otherwise excluded due to issues with fit). The analysis revealed a significant effect of Proportion Congruency, *Est.* = 1.49, *SE* = 0.65, $z = 2.30$, $p < .05$, such that accuracies were higher in the Mostly Incongruent condition, and Sentence Ambiguity, *Est.* = 2.24, *SE* = 0.68, $z = 3.29$, $p < .01$, such that accuracies were higher for Unambiguous sentences, but their interaction was not significant, *Est.* = 0.99, *SE* = 1.16, $z = 0.85$, $p = .40$.

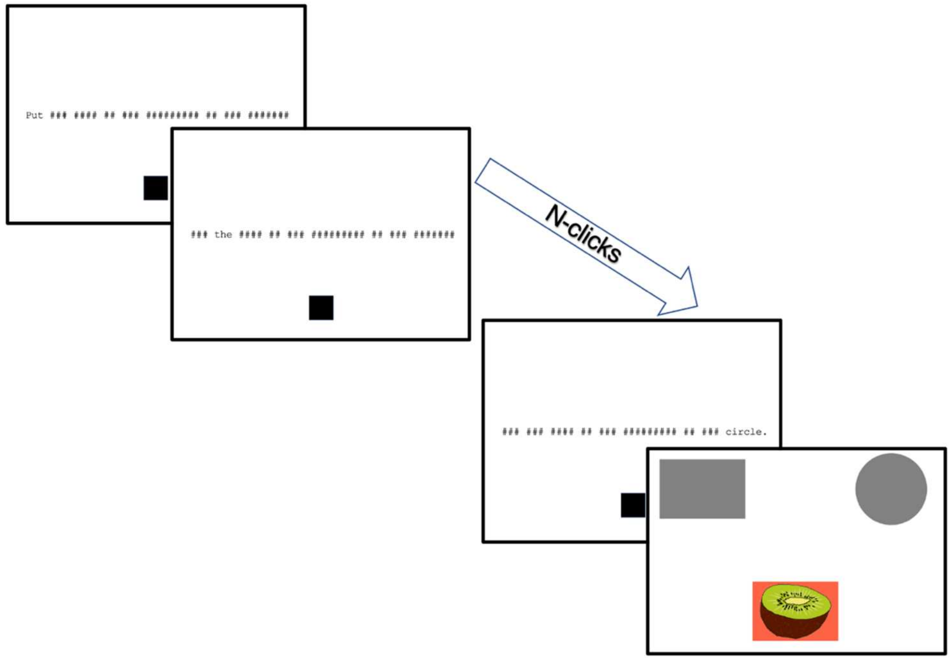

Figure 5. Example visual array and sentence from Experiment 2. Participants read the sentence and then used their mouse cursor to follow the instruction (i.e. clicking and draging the kiwi to the circle).

Third, the impact of proportion congruency on participants' word-by-word sentence RTs (see Figure 6) was analysed. RTs on the modifier (i.e. reflecting the word just before disambiguation, when effects were expected to emerge), "on", "the" and the destination, which were log transformed, were submitted to mixed effect models with fixed effects of Proportion Congruency, Sentence Ambiguity and their interaction, and random intercepts and slopes by participants and items (which were simplified when there were issues with fit). Inaccurate sentence trials, as well as word RTs more than 2.5 standard deviations above the corresponding global word mean, were excluded. Results are reported in Table 4. The analysis revealed a significant interaction of Proportion Congruency and Sentence Ambiguity during "on", such that garden path effects were more pronounced in the Mostly Congruent than Most Incongruent condition. Alongside this interaction, the analysis also revealed a closely related garden path effect across conditions during the remaining words.

Fourth, the impact of proportion congruency on participants' trajectories was analysed. Inaccurate sentence trials, as well as trials with log trajectory RTs more than 2.5 standard deviations above the global mean (1.71%), were excluded from this analysis. Trajectories were aggregated across normalised time slices (e.g. see Experiment 1). Mean trajectories are plotted by Proportion Congruency condition in Figure 2C and D. Mean signed deviations across normalised time from the line connecting the start and end of each within-trial trajectory were also computed (i.e. in contrast to Experiment 1, trajectories were not time locked to unfolding speech). Difference curves (i.e. for ambiguous minus unambiguous sentences) are plotted by Proportion Congruency condition in Figure 4B. Growth curve results are reported in Table 5 and depicted in Figure 4B. The analysis included random slopes for the linear term by participants (slopes were otherwise excluded due to issues with fit). The significant effect of Proportion Congruency on the linear, quadratic and cubic terms indicates that proportion congruency impacted the curvature of participants' difference curves, as reflected in the steeper peak of the Mostly Congruent than Mostly Incongruent condition (e.g. see the right of Figure 4B).

Finally, the results of the growth curve analysis were also confirmed by a simplified MD analysis (e.g. see

Table 3. Experiment 2: Mean Stroop accuracies and RTs by proportion congruency and trial congruency condition.

	Accuracy (%)		RT (ms)	
	Congruent	Incongruent	Congruent	Incongruent
Mostly Congruent	98.43 (1.78)	99.00 (1.65)	650.90 (89.00)	734.13 (113.66)
Mostly Incongruent	98.95 (1.99)	99.54 (0.83)	711.79 (149.31)	730.50 (164.93)

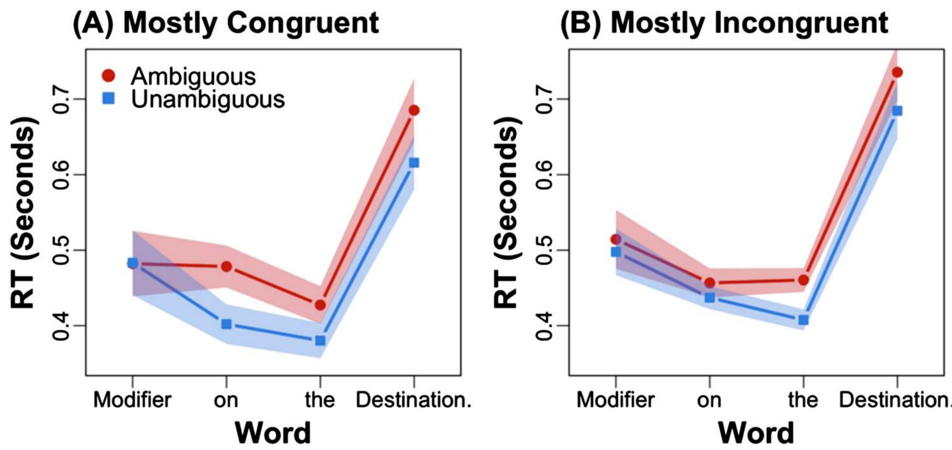

Figure 6. Experiment 2: Word-by-word RTs for ambiguous and unambiguous sentences in the mostly congruent (A) versus incongruent (B) condition.

Experiment 1) focused on the final quartile of the normalised time window (>75%), when the difference curves diverged maximally (e.g. see Figure 4B). The analysis included random intercepts by participants and items (slopes were excluded due to issues with fit). The analysis revealed a significant interaction of Proportion Congruency and Sentence Ambiguity, $Est. = 0.04$, $SE = 0.02$, $t(1073) = 2.50$, $p < .05$, such that garden path effects were more pronounced in the Mostly Congruent (Ambiguous $M = 0.08$, $SD = 0.10$; Unambiguous $M = 0.04$, $SD = 0.03$) than Mostly Incongruent (Ambiguous $M = 0.04$, $SD = 0.04$; Unambiguous $M = 0.05$, $SD = 0.05$) condition.

Discussion

Mirroring Experiment 1, Experiment 2 yielded three key results: Stroop RT effects were reduced in the Mostly Incongruent compared to Mostly Congruent condition; garden path mouse cursor effects were observed with Ambiguous compared to Unambiguous sentences; and garden path effects were reduced in the Mostly Incongruent compared to Mostly Congruent condition. Consistent with Experiment 1 and Hsu and Novick (2016), these results support a causal link between cognitive control and syntactic ambiguity resolution. Novelly, these results also extend prior research by revealing that cognitive control supports reading comprehension, spanning both spoken and written modalities.

Interestingly, Experiment 2 revealed both immediate (i.e. word-by-word RT effects as participants read sentences) and delayed (i.e. mouse cursor effects as participants performed these actions) impacts of sentence ambiguity and proportion congruency. At disambiguation (i.e. "on"), word-by-word RTs were less disrupted in the Mostly Incongruent than Mostly Congruent condition, suggesting that engagement of cognitive control in the former immediately facilitated the reinterpretation of the garden path ambiguity. In addition, while performing the action after a short delay (i.e. after sentence offset), mouse cursor movements were less disrupted (i.e. as reflected in deflections to incorrect objects) in the Mostly Incongruent than Mostly Congruent condition, suggesting that engagement of cognitive control in the former was sustained through to the subsequent mouse cursor response.

Table 4. Experiment 2: Analysis of word-by-word RTs.

Word	Fixed effect	*Est. (SE)*	*t*	*p*
Modifier	Proportion	0.08 (0.11)	0.76	.45
	Ambiguity	0.00 (0.02)	−0.20	.84
	Pro x Amb	−0.02 (0.05)	−0.36	.72
"on"	Proportion	0.05 (0.07)	0.76	.45
	Ambiguity	−0.09 (0.03)	−3.51	< .001
	Pro x Amb	0.12 (0.05)	2.39	< .05
"the"	Proportion	0.10 (0.06)	1.57	.12
	Ambiguity	−0.10 (0.02)	−4.24	< .001
	Pro x Amb	−0.01 (0.05)	−0.15	.88
Destination	Proportion	0.10 (0.07)	1.30	.20
	Ambiguity	−0.07 (0.03)	−2.43	< .05
	Pro x Amb	0.03 (0.06)	0.57	.57

Table 5. Experiment 2: Growth curve analysis of the (ambiguous – unambiguous) difference curves in the mostly congruent versus mostly incongruent condition.

Fixed effect	*Est. (SE)*	*t*	*p*
Intercept	1.89 (0.63)	3.00	< .01
Linear	0.84 (2.02)	0.41	.68
Quadratic	−15.13 (0.85)	−17.84	< .001
Cubic	−0.32 (0.85)	−0.37	.71
Proportion	−1.15 (1.26)	−0.91	.37
Pro x Linear	−8.55 (4.05)	−2.11	< .05
Pro x Quadratic	7.38 (1.70)	4.35	< .001
Pro x Cubic	11.67 (1.70)	6.88	< .001

Note. *Est.* and *SE* x 10^{-2}.

General discussion

Two experiments investigated the effect of sustained cognitive control engagement on syntactic ambiguity resolution. Using a proportion congruency manipulation (e.g. Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979), participants' cognitive control was engaged (i.e. and sustained) experimentally by interleaving sentence trials among either mostly incongruent or mostly congruent Stroop trials. Complementing this proportion congruency manipulation, each sentence trial was also preceded by an incongruent Stroop trial in the mostly incongruent condition or congruent Stroop trial in the mostly congruent condition. Participants heard (Experiment 1) or read (Experiment 2) garden path sentences and their mouse cursor trajectories and word-by-word RTs (i.e. in the latter) were measured. Crucially, reduced garden path effects were observed in the mostly incongruent as compared to mostly congruent condition: across both experiments, mouse cursor movements deviated less to incorrect destinations like an empty rectangle with sentences like "Put the kiwi on the rectangle on the circle", and in Experiment 2, word-by-word RTs were also slowed less from disambiguation. These experiments yield two novel insights into syntactic ambiguity resolution: first, the current manipulation supported the engagement of cognitive control and clearly, robustly and causally improved sentence comprehension across (i.e. spoken and written) modalities; and second, motor movements of the hand were sensitive to the experimental engagement of cognitive control.

The current results complement the research of Novick and colleagues. Both visual world eye tracking (e.g. Hsu & Novick, 2016; Hsu et al., 2021; Thothathiri et al., 2018) and event-related brain potentials (e.g. Ovans et al., 2022) reveal that experimentally engaging cognitive control improves sentence comprehension, supporting a causal link between the two that extends beyond mere individual differences correlations. Hsu and Novick (2016) and Hsu et al. (2021) interleaved garden path sentences among Stroop and Flankers trials, respectively. Hsu et al.'s (2021) participants made more eye movements to correct than incorrect destinations when their cognitive control was engaged (e.g. scarf vs. binder when hearing sentences like "Put the horse on the binder onto the scarf"), paralleling the more direct mouse cursor movements to correct destinations in the current experiments. Hsu et al. (2021) also observed effects on participants' sentence accuracies, whereas no such effect was observed in the current experiments. Rather, the current participants' sentence accuracies were near ceiling, which may be explained by the considerably simpler current visual arrays.

In contrast, the current results are at odds with prior findings showing that performance is not improved when sentence trials are preceded by incongruent as compared to congruent Stroop trials (e.g. Kan et al., 2013; Patra et al., 2023; Simi et al., 2023). A range of explanations for these mixed findings has been discussed in the literature. Central to the current investigation, Kan et al. (2013) highlight the time separating Stroop trials from critical points (e.g. disambiguation) in sentence trials, during which cognitive control may disengage (see also temporal momentum; Ness et al., 2023). We conjecture that the current use of a list-wide proportion congruency manipulation may shed new light on the mixed findings in the literature, which have previously used manipulations rooted in the congruency sequence effect (i.e. which focuses on conflict adaptation across back-to-back trials; Gratton et al., 1992). In blocks with a high proportion of conflict trials, cognitive control is hypothesised to be actively engaged over a considerable span of time and sustained proactively across an experiment (e.g. Braver et al., 2007). In contrast, congruency sequence effects reflect the engagement of cognitive control across only back-to-back trials (e.g. Gratton et al., 1992), which is a relatively short period of time (e.g. Duthoo et al., 2014; Egner et al., 2010; for a comprehensive review of research into proportion congruency and congruency sequence effects, see Bugg, 2017; Egner, 2017). Thus, while prior research focuses on the immediately preceding Stroop trial, we conjecture that the longer-term history of Stroop trials, which is emphasised in the current experiments, is also important. In fact, even when there are equal numbers of incongruent and congruent Stroop trials (e.g. as in Hsu & Novick, 2016; Kan et al., 2013), responding to many incongruent trials over the course of an experiment may engage cognitive control in a sustained manner that blurs the distinction between sentences immediately preceded by incongruent vs. congruent Stroop trials, which may contribute to the mix of findings in the literature. We do not doubt that congruency sequence manipulations can be used to engage cognitive control, as is supported by psycholinguistic evidence (e.g. Hsu & Novick, 2016; Hsu et al., 2021; Ovans et al., 2022; Thothathiri et al., 2018), and the wider literature (e.g. Freitas et al., 2007). However, manipulating proportion congruency (i.e. via mostly incongruent vs. mostly incongruent blocks), as in the current research, may engage cognitive control in a particularly robust way because it is less susceptible to decay over time. When processing sentences that unfold over time, this robust sustained engagement may thus provide particularly clear insight into the link between cognitive control and sentence comprehension.

However, the current design does not experimentally distinguish effects emerging across blocks of trials (i.e. via the proportion congruency manipulation) vs. back-to-back trials (e.g. see conflict adaptation; Gratton et al., 1992). Rather, the current design supported the sustained engagement of participants' cognitive control by leveraging effects emerging across both blocks of trials as well as back-to-back trials (i.e. each sentence trial was also preceded by an incongruent Stroop trial in the mostly incongruent condition or congruent Stroop trial in the mostly congruent condition), which were thus confounded. Whether the current results depended on sustained engagement of cognitive control across the experiment, or engagement across back-to-back trials, or a combination of both, is thus unresolved. Moreover, although these two effects are theorised to work differently, with proportion congruency affecting a more global, proactive level (Bugg, 2017) and conflict adaptation (e.g. Gratton et al., 1992) influencing a more reactive, trial-by-trial level (Egner, 2017) it is possible that they interact. For example, an open question is how performance may be impacted when cognitive control is engaged in the high proportion condition but preceded by a congruent rather than incongruent trial. Thus, an important direction for future research will be to de-confound effects emerging across blocks of trials vs. back-to-back trials, which would also further shed light on the levels of processing supporting incremental sentence comprehension and ambiguity resolution. Relatedly, our proportion congruency manipulation was between participants, while congruency sequence manipulations (i.e. which focus on conflict adaptation across back-to-back trials; Gratton et al., 1992) are typically within participants. It may also be worthwhile to assess proportion congruency effects within participants (e.g. across blocks). For example, although participants were randomly assigned to conditions in the current experiments, individual differences could still contribute to the observed differences.

The current design also focuses on Stroop to manipulate cognitive control. Hsu et al. (2021) highlight two relevant concerns: first, Stroop (i.e. classically) presents language, so an open question is whether the observed links are domain general; and second, Stroop requires control and attention, which may be separable, so an open question is whether the observed links depend on control. Thus, it may also be worthwhile to assess other cognitive control manipulations (e.g. tasks), such as Flankers. Relatedly, the current design focused on syntactic ambiguities rather than other language phenomena. Thus, another important direction for future research will be to address the specificity of these results (e.g. to syntactic ambiguity resolution), particularly compared to other sentence manipulations that are not hypothesised to require cognitive control (e.g. which may support more generalised explanations, like motivation; Christianson et al., 2022). For example, Hussey et al. (2015) engaged cognitive control experimentally using transcranial direct current stimulation (tDCS) and observed effects specific to a garden path but not relative clause manipulation.

These results also add to Novick and colleagues' findings by revealing links between cognitive control and reading comprehension. On the one hand, Patra et al. (2023) and Simi et al. (2023) both used self-paced reading (e.g. see also Kan et al., 2013), and neither observed effects of cognitive control engagement on reading times. Thus, cognitive control may be less important for reading comprehension. On the other hand, the Stroop task, which provides an important index of cognitive control, is closely tied to reading. Compellingly, Experiment 2 revealed clear effects of cognitive control engagement on reading times, which paralleled the effects on mouse cursor movements in Experiment 1 and eye movements in prior research (e.g. Hsu & Novick, 2016). These results also complement Ovans et al. (2022), who presented written text (i.e. at a constant rate), but measured ERPs rather than reading times. While Ovans et al. (2022) focused on conflicts between syntax and semantics during reading, the current results yield new insight into the processing of garden path conflicts during reading. Crucially, these results suggest that comprehension is causally supported by cognitive control across (i.e. spoken and written) modalities.

Relatedly, an important difference between prior reading studies (e.g. Kan et al., 2013) and the current research is that participants were always required to perform the described action, similar to prior spoken language studies (e.g. Hsu & Novick, 2016). In contrast, prior reading studies like Kan et al. (2013), which failed to replicate a link between cognitive control and sentence comprehension, measured participants' comprehension by asking them probe questions, and only after filler sentences. This difference might also contribute to the mixed findings in the literature because the benefits of heightened levels of cognitive control might only be revealed against the additional requirements of planning and executing an action.

The reading time and mouse cursor effects observed in Experiment 2 have important theoretical implications as well. We conjecture that these effects, which occurred sequentially in Experiment 2, support Good Enough approaches to language comprehension (e.g. Christianson et al., 2001; Ferreira et al., 2002; Ferreira & Patson, 2007). According to Good Enough approaches, instead of achieving a detailed, complete, and accurate understanding, the language comprehension system creates representations only to a level that is "good enough" for performing the subsequent task and refined only if necessary. Thus, garden path misinterpretations (e.g. incorrectly interpreting an empty rectangle as the destination when hearing "Put the kiwi on the rectangle on the circle") may still be active even after disambiguation, and these representations may have influenced behaviour during the subsequent mouse cursor response in Experiment 2. Interestingly, we observed mouse cursor (i.e. garden path) effects on accurate sentence trials even in Experiment 2 (e.g. see Figure 3C and D), which suggests that even when reanalysis yields a grammatical parse, it may nevertheless fail to "clean up" lingering misinterpretations (e.g. see Slattery et al., 2013). Relatedly, proportion congruency designs, in which sentence trials are presented infrequently relative to Stroop trials, might also further promote "good enough" processing. Compared to congruency sequence designs that interleave Sentence and Stroop trials one-to-one (i.e. and focus on conflict adaptation across back-to-back trials; Gratton et al., 1992), the lower frequency of sentence trials in the current research could result in greater challenges for goal maintenance (Duncan et al., 1996), which utilises proactive control (Paxton et al., 2008), particularly on sentence trials. The current results are also compatible with a recent model proposed by Ness et al. (2023), which hypothesises that cognitive control is supported by both monitoring and biasing subsystems. The current results may place particular emphasis on the monitoring subsystem's sensitivity to conflict at multiple scales, including the current sentence trial, the immediately preceding Stroop trial and the preceding block of Stroop trials.

Finally, the current experiments demonstrate that internet-mediated methods are a powerful tool for investigating the mechanisms underpinning incremental language processing and ambiguity resolution. Novick and colleagues have compellingly linked cognitive control and sentence comprehension using lab-based methods, including visual world eye tracking (e.g. Hsu & Novick, 2016; Hsu et al., 2021; Thothathiri et al., 2018) and event-related brain potentials (e.g. Ovans et al., 2022). In contrast, evidence from internet-mediated studies, including Aczel et al. (2021), Dudschig (2022), Patra et al. (2023) and Simi et al. (2023), has cast doubt on this link. However, an important difference that may contribute to this mix of findings is their samples. Lab-based methods typically rely on (e.g. WEIRD; Henrich et al., 2010a, 2010b) samples that may be problematic to generalise. In contrast, internet-mediated methods have a long history in experimental psychology (e.g. Reips, 2002), and can be "as good as the lab" (e.g. Germine et al., 2012), but reach wider and more diverse populations. Crucially, the current results suggest that comprehension is causally supported by cognitive control even outside a lab-based undergraduate sample (i.e. see Experiment 2). Again, we conjecture that manipulating proportion congruency, as in the current research, may sustain cognitive control engagement, such that it is less susceptible to decay over time. Relatedly, uncontrolled environments outside the lab may also be particularly susceptible to decay (e.g. see congruency sequence effects, which focus on conflict adaptation across back-to-back trials; Gratton et al., 1992), which may thus account for the contrasting findings of Aczel et al. (2021), Dudschig (2022), Patra et al. (2023) and Simi et al. (2023). Taken together, the current results suggest that internet-mediated methods are well suited to addressing the role of cognitive control in sentence comprehension.

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Data availability statement

The data is available in OSF: https://osf.io/6qa8v.

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