Neural Mechanisms of Adult Bilingual Syntactic Ambiguity Resolution

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1. Introduction

1.1. Syntactic ambiguity resolution in adults

Sentence comprehension proceeds incrementally, with listeners rapidly integrating syntactic structure, lexical information, and contextual cues as an utterance unfolds (Altmann & Kamide, 1999). This incremental processing can lead listeners to commit to an initially preferred interpretation that later turns out to be incorrect. In such cases, successful comprehension requires revision of the initial parse in favor of the ultimately correct structure (Choi & Trueswell, 2010).

Classic garden-path sentences illustrate this phenomenon. For example, in sentences such as *Put the frog on the napkin into the box*, listeners initially tend to interpret the first prepositional phrase (*on the napkin*) as the destination rather than as the modifier. Behavioral work shows that adults can revise this initial commitment once disambiguating information becomes available, successfully recovering from the garden path (Trueswell et al., 1999).

Early accounts of such effects emphasized structural heuristics, such as the Garden-Path Model and Minimal Attachment (Frazier & Rayner, 1982), which propose that listeners initially construct the syntactically simplest structure available. While these models capture initial parsing preferences, adult performance demonstrates flexibility beyond these constraints, particularly when revision is required.

More work has emphasized the role of contextual and probabilistic information in guiding parsing decisions. The Referential Principle (Altmann & Steedman, 1988) proposes that when the visual or discourse context supports a more complex structure, listeners can adopt that structure without increased processing difficulty. Indeed, adults readily integrate referential information to disambiguate prepositional phrase attachment, using context to support modifier interpretations when multiple referents are present (Trueswell et al., 1999).

Together, these findings support constraint-based accounts of sentence processing, which propose that multiple sources of information are weighted interactively during comprehension (Chambers et al., 2004; Novick et al., 2008; Pearlmutter & Macdonald, 1995). Under these accounts, adult syntactic ambiguity resolution reflects competition among alternative representations rather than the results of incremental processing alone.

 Proceedings of the 50th annual Boston University Conference on Language Development, ed. Romi Hill et al., 390-403. Somerville, MA: Cascadilla Press.

1.2. Cognitive control in syntactic ambiguity resolution

Resolving syntactic ambiguities places demands on domain-general cognitive resources, particularly when initial interpretations must be inhibited or revised. Individual differences studies show that adults with greater working memory capacity or reading span are better able to integrate multiple constraints and recover from dispreferred parses (Novick et al., 2008; Pearlmutter & Macdonald, 1995). Neuroimaging work further demonstrates that individuals with higher syntactic and semantic working memory capacity show more focal recruitment of language-related brain regions, like left inferior frontal gyrus (IFG), during ambiguity resolution (Fiebach et al., 2004).

A growing body of work directly links syntactic ambiguity resolution to cognitive control mechanisms. Behavioral training studies demonstrate that improving conflict resolution abilities, particularly through tasks that require interference suppression, such as the *n*-back task with lures, leads to improved online processing of syntactically ambiguous sentences (Novick et al., 2014; Teubner-Rhodes et al., 2016). These findings suggest that ambiguity resolution relies on the ability to monitor conflict between interpretations and suppress an initially dominant, but ultimately incorrect, parse.

Neuroanatomically, general language processing recruits a left-lateralized network, including temporal regions (superior temporal gyrus (STG), and middle temporal gyrus (MTG)), frontal regions (IFG, and middle frontal gyrus (MFG)), and parietal regions (inferior parietal lobe (IPL), and angular gyrus) (Friederici, 2012; Lau et al., 2016). Within this network, the left IFG and MTG have been repeatedly implicated in syntactic unification, reanalysis, and selection among competing representations (Acheson & Hagoort, 2013; January et al., 2009).

Activity in the left IFG is modulated by processing demands and individual differences in cognitive control, and it overlaps substantially with regions recruited during non-linguistic conflict resolution tasks (Hsu et al., 2017; January et al., 2009). This has led to proposals that left IFG functions as a domain-general control "hub" that dynamically interacts with language-specific networks depending on task demands (Acheson & Hagoort, 2013; Hsu et al., 2017).

Additional regions implicated in ambiguity resolution include the anterior cingulate cortex (ACC), pre-supplementary motor area (pre-SMA), anterior insula, intraparietal sulcus, and precuneus, suggesting that syntactic reanalysis engages broader attention and conflict monitoring networks (Bornkessel-Schlesewsky et al., 2009).

1.3. Cognitive control, bilingualism, and ambiguity resolution

Bilingual language use provides a natural context in which cognitive control is continuously engaged, especially given the evidence that both languages remain active and must be regulated to avoid interference (Van Heuven et al., 2008). Neuroimaging studies show that bilingual language control recruits a network that

includes left IFG, STG, IPL, pre-SMA, insula, and ACC, all of which overlap with domain-general cognitive control systems (De Baene et al., 2015).

This overlap has motivated theoretical accounts, such as the Adaptive Control Hypothesis (Green & Abutalebi, 2013), which proposes that sustained bilingual language use leads to adaptations in control-related brain networks, but that these adaptations vary depending on specific bilingual experience. These adaptations may be reflected in functional efficiency, structural changes, or connectivity differences within regions such as IFG, ACC, IPL, and subcortical nuclei (Abutalebi & Green, 2016).

Consistent with this view, bilingualism has been associated with differences in gray matter volume and white matter connectivity in frontal, temporal, and parietal regions involved in language control (García-Pentón et al., 2016; Pliatsikas, 2020). However, evidence for a consistent behavioral bilingual advantage in cognitive control is mixed, with many studies reporting neural differences in the absence of performance differences (Brothers et al., 2021; Hilchey & Klein, 2011).

Importantly, bilingualism has also been shown to modulate the relationship between cognitive control training and syntactic ambiguity resolution. Balanced bilingual adults exhibit greater benefits from conflict resolution training when processing temporarily ambiguous sentences, particularly under high-conflict conditions (Teubner-Rhodes et al., 2016). These findings suggest that bilingual experience may enhance the efficiency or flexibility with which control mechanisms are deployed during language processing, even if behavioral outcomes appear comparable to monolinguals.

1.4. The current study

Across behavioral and neuroimaging studies, successful syntactic ambiguity resolution in adults is consistently linked to the ability to manage competing representations and revise initial misinterpretations. This process relies on interaction between core language networks and domain-general cognitive control systems, with left IFG playing a central role.

Bilingualism provides a compelling lens through which to examine these mechanisms, as bilingual language use engages and potentially reshapes control networks that overlap with those implicated in syntactic reanalysis. While behavioral evidence for a bilingual advantage remains mixed, converging neuroimaging findings suggest that bilinguals may differ in how efficiently or flexibly they recruit control-related brain regions during language processing.

With this in mind, the present work examines how adult monolinguals and bilinguals recruit neural networks during syntactic ambiguity resolution, focusing on contrasts that isolate the presence of ambiguity and revision mechanisms. By integrating behavioral tendencies with functional activation patterns, this study aims to clarify how bilingual experience modulates the neural mechanisms supporting syntactic ambiguity resolution.

2. Methods

2.1. Participants

Twenty-seven adults participated: 24 English monolinguals and 8 English-Hawaiian bilinguals (Table 1). All had normal hearing and normal or corrected vision. Monolinguals spoke only English. Bilinguals acquired Hawaiian before age 6 years, used it regularly throughout childhood, and continue to speak it at home and/or work; all were English-dominant. Language background was assessed using the Household Adult Language Profile (Deen et al., 2025).

Table 1. Participant demographics by group.

Group	n	Mean age (range)	% Female	Age of Hawaiian exposure	Language Experience
Monolingual adults	24	24.5 (18–45)	83	NA	Native English speakers; no other languages
Bilingual adults	8	29.6 (18–444)	63	6	Hawaiian learned in school or at home; most were English-dominant

Procedures followed institutional ethical standards and the revised Helsinki Declaration (2008). Informed consent was obtained.

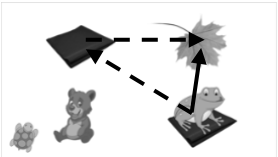
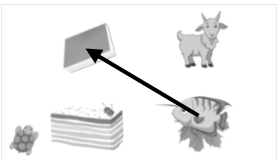
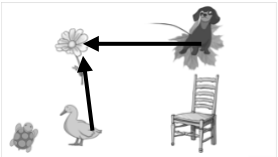
2.2. Materials

Tasks were presented in English using Presentation software (v24.0; Neurobehavioral Systems, Inc.) and framed around a cartoon turtle, Buzz. Stimuli were recorded by native English speakers in a soundproof booth using Praat (Boersma & Weenink, 2021).

2.2.1. Action verification (AV) task

The AV task assessed comprehension of garden-path sentences (Trueswell et al. 1999). Ambiguous sentences (e.g., *Put the frog on the napkin onto the book*) were paired with scenes showing a target animal, distractor animal, correct destination, and distractor destination (Table 2a). Unambiguous control sentences used the same, two-prepositional-phrase structure but the distractor destination was an unmentioned object (Table 2b). Fillers involved moving two animals to a single destination and started with, *Move* (Table 2c).

Table 2. Examples of sentences for the AV task. Solid arrow is the correct action, dashed arrow is the incorrect action, with the continuation from the dashed arrow being the "hopping" action.

Condition	Sentence	Images
a) Ambiguous	Put the frog on the napkin onto the leaf.	
b) Unambiguous	Put the fish on the leaf onto the book.	
c) Filler	Move the duck and the dog onto the flower.	

Each trial presented the sentence word-by-word (400 ms inter-word interval; 500-1000ms jitter around the critical word) while the starting scene appeared. Participants then judged whether Buzz's action matched the sentence (RIGHT/WRONG). Two lists of 108 sentences (36 in each condition) were counterbalanced for correctness, image position, and action direction.

2.2.2. Picture selection (PS) task

This task tested prepositional phrase attachment ambiguities (Kidd & Bavin, 2005). Ambiguous sentences (e.g., *The woman waved to the man with the flag*) may have instrument (VP) or modifier (NP) readings. Unambiguous controls had clear VP or NP readings. Fillers included subject attachment and conjoined clauses (Table 3). Participants selected between two illustrations.

The task included 108 sentences: 36 ambiguous, 24 unambiguous – VP, 24 unambiguous – NP, 12 subject-attachment fillers, and 12 conjoined clause fillers. Sentences were balanced for activity vs perceptual verbs and the preposition *with* vs locative prepositions. Participants were assigned to one of two lists counterbalanced for image position.

Trials began by introducing the images, followed by word-by-word sentence presentation (200 ms inter-word interval), and image selection.

Table 3. Examples of sentences and images in the PS task.

Condition	Sentence	Image 1	Image 2
a) Ambiguous	The woman waved to the man with the flag.		
		Instrument interpretation	Modifier interpretation
b) Unambiguous – VP	The girl poked the cat with the stick.		
c) Unambiguous – NP	The boy moved the doll with the red hair.		
d) Filler – subject attachment	The seal with the hat tasted the fruit.		
e) Filler – conjoined clause	The musician wrote the song and the letter.		

2.2.3. Procedure

Participants completed 2 MRI sessions, each including two task runs, a T1-weighted scan, and two additional task runs. Task blocks contained 18 trials and task order was counterbalanced. Audio stimuli were delivered via MR Compatible Sensimetrics S14 earphones. MRI sessions lasted about 90 minutes, with 45 minutes in the MRI scanner.

2.3. Behavioral analysis

Accuracy was coded as 1 (correct/instrument interpretation) and 0 (incorrect/modifier interpretation). All participants performed above 50% for unambiguous and filler items, so none were excluded.

Data were analyzed using mixed-effects logistic regression in R (*lme4*; Bates et al., 2015). Predictors were sum-coded and included language (bilingual, monolingual), and condition (ambiguous, unambiguous, filler), with interactions as appropriate. Maximal random-effects structure included by-item and by-participant intercepts and slopes. Models that did not converge were simplified following Barr et al. (2013) and Matuschek et al. (2017).

Separate models were fit for each task. For the PS task, ambiguous items were analyzed by verb and preposition type, with predictors sum-coded. For the AV task, predictors included language group and condition. Significance was set at $p < .05$. No effects of list were found, so data were combined.

2.4. Image acquisition

Imaging data were acquired on a 3T Siemens Prisma (Erlangen, Germany) with a 64-channel head coil. T1-weighted anatomical images were collected using MPRAGE (192 slices, TR = 2530 ms, TE = 3.37 ms, flip angle = 7 degrees, 1 mm isotropic). Functional images used a multi-band multi-echo echo-planar imaging (EPI) event-related sequence (TR = 1500 ms, TE = 13.4/34.6/55.78 ms, flip angle = 70 degrees, voxel size = 2.5 mm isotropic, 51 slices). The first five volumes of each run were discarded.

2.5. fMRI analysis

Functional image preprocessing and analyses were conducted in AFNI (v25.0.07; Cox, 1996) using *afni_proc.py*. Preprocessing included slice-time correction, motion correction, alignment to the MNI152_2009 template, and 4 mm full-width half-max (FWHM) Gaussian smoothing. First-level single-subject regressions generated contrasts of interest: for the AV task, Ambiguous post-critical word – Ambiguous pre-critical word (Apostcrit – Aprecrit) and Ambiguous – Unambiguous (A – U); for the PS task, Ambiguous – Unambiguous (A – U). Participants with over 15% of volumes censored due to motion were excluded (n = 4).

Group-level analyses used *3dttest++* with cluster correction (Cox et al., 2017), which performs voxel-wise two-sample t-tests to compare monolinguals and bilinguals. Voxels were restricted to a group-level brain mask. Each subject contributed one contrast map per relevant comparison for a group-model with by-subject random-effects.

3. Results

3.1. Behavioral results

Both bilingual and monolingual adults performed comparably in each task, yielding no effects of bilingualism ($p > .293$ for all terms). In the action verification (AV) task, we found an effect of condition (*Odds Ratio* = 0.15, $t = -5.19$, $p < .001$), with participants performing worse in the ambiguous condition compared to unambiguous and filler conditions.

In the picture selection (PS) task, we ran three separate analyses. First, we found no effects of language or condition on accuracy for unambiguous or filler items ($p > .9$ for all terms). Second, we found no effect of preposition type or language on instrument attachment preferences ($p > .293$ for all terms). Third, we found a significant main effect of verb type (*Odds Ratio* = 2.87, $t = 2.80$, $p = .005$), revealing that participants had a higher tendency to interpret the prepositional phrase as an instrument when the verb was an activity verb. The interaction between language and verb type was not significant.

3.2. Garden-path sentence resolution - fMRI

To process garden-path ambiguities, both groups recruited an overlapping network that included a small portion of lateral and medial superior frontal gyrus (SFG), IFG pars triangularis, and insula on the left hemisphere, and an anterior part of supramarginal gyrus (SMG) (Figure 1a). Bilinguals showed greater activation in posterior and subcortical regions, including bilateral pre- and postcentral gyri, pre-SMA, supplementary motor areas (SMA), SMG, and left caudate and putamen (Figure 1b, darker grays). Bilinguals also showed reduced activation in left angular gyrus and insula, and bilateral SFG, MFG, and MTG (Figure 1b, lighter grays).

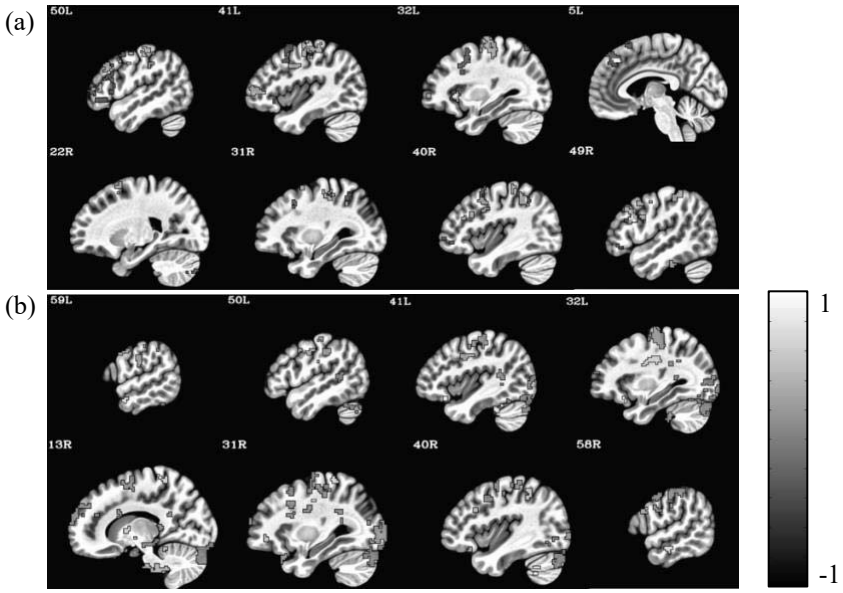


Figure 1. Ambiguous > Unambiguous contrast in the AV task. (a) Overlapping and group-specific activation (monolingual = dark gray; bilingual = light gray; overlap = white). (b) Monolingual > bilingual (lighter grays) and bilingual > monolingual (darker grays) contrasts. Clusters are thresholded at $p < .05$ with cluster-level correction.

During the post-critical word window (syntactic revision), both groups activated large portions of bilateral MFG, SFG, and IFG, as well as MTG, STG, pre- and postcentral gyri, and bilateral superior parietal lobe (SPL) (Figure 2a).

In this window, bilinguals showed stronger and more spatially focal activation in each overlapping region, suggesting more selective engagement of revision mechanisms. We see this specifically in left IFG pars triangularis, SPL, IPL, right inferior temporal gyrus (ITG), right ACC, and bilateral postcentral gyri and precuneus (Figure 2b).

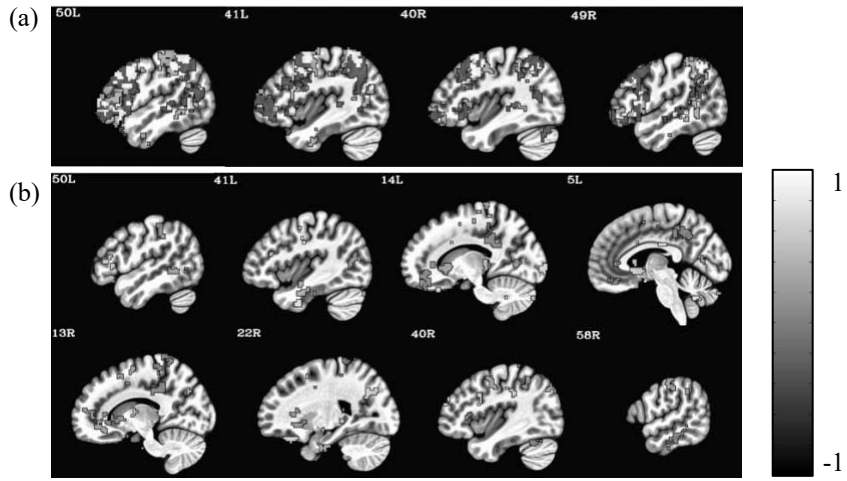


Figure 2. Post-critical > pre-critical word contrast in the ambiguous condition of the AV task. (a) Overlapping and group-specific activation (monolingual = dark gray; bilingual = light gray; overlap = white). (b) Bilingual > monolingual (darker grays) contrast. Clusters are thresholded at $p < .05$ with cluster-level correction.

3.3. Prepositional phrase attachment ambiguities - fMRI

For prepositional phrase attachment ambiguities, both groups activated bilateral SFG, MFG, and IFG, IPL, as well as right insula, and right precuneus for ambiguous sentences (Figure 3a). Monolinguals showed more extensive activation in bilateral STG, MTG, and precuneus, left SFG, SMG and postcentral gyrus, and right precentral gyrus (Figure 3b, lighter grays). Bilinguals, by contrast, showed more restricted activation, primarily in bilateral precentral gyrus and an anterior portion of left MFG (Figure 3b, darker grays).

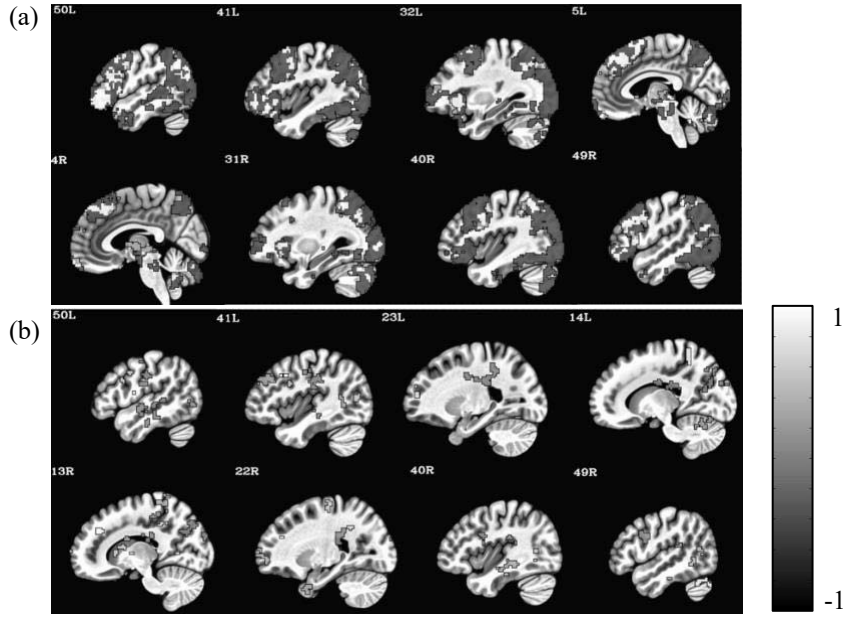


Figure 3. Ambiguous > Unambiguous contrast in the PS task. (a) Overlapping and group-specific activation (monolingual = dark gray; bilingual = light gray; overlap = white). (b) Monolingual > bilingual (lighter grays) and bilingual > monolingual (darker grays) contrasts. Clusters are thresholded at $p < .05$ with cluster-level correction.

Across tasks, bilinguals consistently exhibited less intense and more focal recruitment of ambiguity-related networks, indicating that bilingualism modulates how core language-control systems are engaged, rather than which systems are recruited.

4. Discussion

The present study examined whether bilingual experience modulates neural mechanisms supporting comprehension of syntactically ambiguous sentences. Behaviorally, bilingual and monolingual adults performed comparably across both tasks, showing no group differences in garden-path sentence accuracy (AV task) or prepositional phrase attachment interpretation preferences (PS task). This convergence allows the observed neural differences to be interpreted as reflecting differences in processing strategies, rather than differences in task success. Neural differences despite comparable behavior have been reported in bilingualism during non-linguistic conflict monitoring, particularly in ACC and IFG engagement (Coderre et al., 2016; Hilchey & Klein, 2011).

Across both tasks, bilinguals and monolinguals recruited overlapping regions in frontal, parietal, and sensorimotor cortices when resolving syntactic ambiguities, indicating a shared network for syntactic processing and revision. However, group differences emerged in the extent and intensity of activation. During garden-path sentence resolution, bilinguals showed relatively greater activation in posterior and subcortical regions (bilateral pre- and postcentral gyri, SMA, SMG, and left caudate and putamen) and reduced activation in angular gyrus, insula, and bilateral SFG, MFG, and MTG. Monolinguals engaged more extensive frontal and temporal association cortices, suggesting reliance on distributed language integration mechanisms.

This pattern is consistent with the bilingual anterior-to-posterior and subcortical shift (BAPSS) (Grundy et al., 2017) model and other theories proposing that lifelong management of linguistic competition tunes neural systems toward efficient, targeted cognitive control engagement (Abutalebi & Green, 2016; Grundy et al., 2017).

Focusing on the post-critical word window, both groups activated an extensive and overlapping set of frontal, temporal, parietal, and sensorimotor regions. Within this shared network, bilinguals exhibited greater activation magnitude but more spatially focal clusters, suggesting more efficient or selective engagement of revision mechanisms. This focal engagement aligns with proposals that bilingual experience refines deployment of control and language networks through repeated management of competing linguistic representations (Abutalebi & Green, 2016; Green & Abutalebi, 2013; Van Heuven et al., 2008).

A similar pattern emerged for prepositional phrase attachment ambiguities. Monolinguals showed more extensive activation across temporal, parietal, and medial regions (STG, MTG, precuneus), whereas bilinguals exhibited more limited increases, primarily in bilateral precentral gyrus and anterior left MFG. Even in the absence of behavioral differences, bilinguals consistently showed more focal recruitment of ambiguity-related networks with differences in activation magnitude depending on mechanism: revision or selection.

These findings suggest that bilingualism does not alter which neural systems support syntactic ambiguity resolution, but how those systems are engaged. Bilinguals appear to rely on a more constrained subset of regions within a shared language-control network, consistent with more selective allocation of processing resources, which may reflect adaptive efficiency from dual-language experience (Abutalebi & Green, 2016; Green & Abutalebi, 2013).

A limitation of the present study is that conclusions about efficiency are inferred from spatial extent and activation magnitude rather than from direct measures of connectivity or temporal dynamics. Further work using functional connectivity or multivariate approaches could clarify whether bilinguals' more focal activation reflects tighter coordination within language-control networks during ambiguity resolution.

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Proceedings of the 50th annual Boston University Conference on Language Development

edited by Romi Hill, Xinhan Jiang, Danutham Worapipat, and Aditya Yedetore

Cascadilla Press Somerville, MA 2026

ISSN 1080-692X
ISBN 978-1-57473-047-0 (2 volume set, paperback)

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