Brain and Language 183 (2018) 47–53

Contents lists available at ScienceDirect

Brain and Language

journal homepage: www.elsevier.com/locate/b&l

Short communication

Statistical experience and individual cognitive differences modulate neural activity during sentence production

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ARTICLE INFO

Keywords:
Language
Speech
Syntactic choice
Executive function
Cognitive control
Anterior cingulate cortex
Frontal cortex

ABSTRACT

I explored how individual cognitive differences combine with prior statistical experience to determine choice of sentence structure during speech. Participants were exposed to English language input with controlled statistical properties wherein some verbs appeared equally often in two possible structures and others appeared in only one. Subsequently, they produced sentences naturally while their brain activity was scanned. Choosing a less preferred over a more preferred structure recruited regions involved in conflict control, especially in individuals with better control abilities. Activity within a key region, the anterior cingulate cortex or ACC, varied parametrically with the statistical input properties. ACC activation showed different correlations with language production and different functional connectivity patterns for different verbs. These results demonstrate how the adult brain adjusts to ongoing language experience and recruits different neural resources to accomplish the same speech goal under different circumstances.

1. Introduction

It is an accepted truism that children's speech varies depending on language exposure and individual differences in cognitive abilities. It is less obvious how these ideas might apply in adulthood. Language learning—not just in a second language, but also in one's native language—continues through the lifespan. The adult brain can track statistical patterns present in the surrounding input and adjust subsequent speech accordingly (Ferreira & Schotter, 2013; Thothathiri & Rattinger, 2015, 2016; Wonnacott, Newport, & Tanenhaus, 2008). Cognitive differences between individuals could impact the nature of these adjustments. Here I provide a novel and concrete demonstration of these ideas by exposing adult native English speakers to precisely controlled English language input and showing interactive effects of that input and individual cognitive differences on the neural correlates of sentence production.

My enquiry focused on choice of sentence structure for expressing a given meaning. English speakers can describe a transfer action using one of two variants (Double-object (DO) dative: *Laila sent John a package*, Prepositional-object (PO) dative: *Laila sent a package to John*). Prior work suggests an overall preference for the PO structure that can be modulated by input statistics—especially, strength of association between specific verbs and DO/PO—and priming due to recent use (Bock & Loebell, 1990; Coyle & Kaschak, 2008; Thothathiri, Evans, & Poudel, 2017). However, on occasion, speakers also override prior experience and recent use to produce the less expected structure. Individual differences in conflict control—an executive function used to resolve interference and override a prepotent representation—might be particularly relevant in such cases.

Conflict control is a cognitive ability that allows individuals to regulate behavior according to a current goal, particularly when that goal contravenes a default preference. For example, in the Stroop task, conflict control is engaged when participants must override the default tendency to read a written word and name the ink color of that word instead (e.g., say *blue* when shown the word "red" in blue ink). Analogously, during sentence production, control abilities could be involved when speakers override a default structure (e.g., PO) and choose the less preferred alternative (e.g., DO). Two recent studies support such a role for conflict control during speech. In these studies, individuals who performed better at Stroop showed higher rates of producing the less common structure (Thothathiri & Rattinger, 2015; Thothathiri et al., 2017). However, this effect was not uniform across all verbs. Individual differences in conflict control interacted with statistical experience, showing a significant correlation with production of the less common structure for verbs with some statistical properties and not others (Thothathiri & Rattinger, 2015; Thothathiri et al., 2017. See more in Discussion).

In the current study, I sought to understand if and how neural activity during sentence production is modulated by statistical experience and conflict control differences between speakers. To this end, I used a training paradigm that allowed me to manipulate participants' statistical experience. During training, participants heard some verbs only in

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https://doi.org/10.1016/j.bandl.2018.06.005
Received 2 August 2017; Received in revised form 8 May 2018; Accepted 12 June 2018

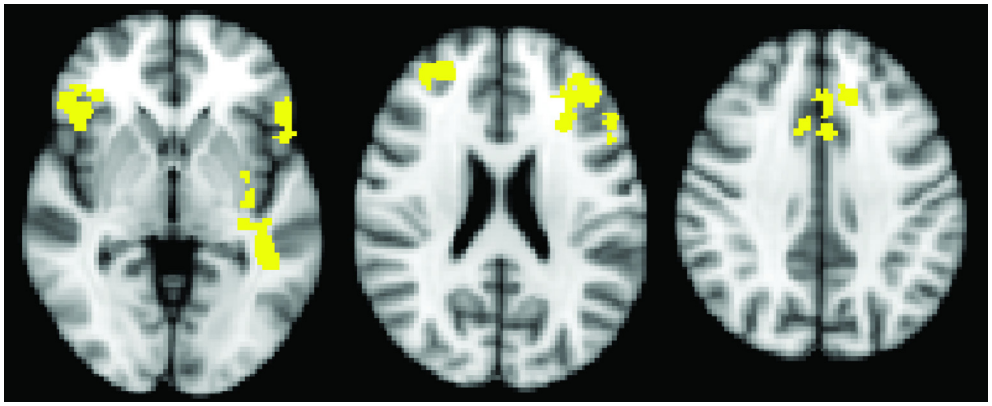

Fig. 1. Brain regions where activation for producing DO after a previous PO was correlated with conflict control ability. Left panel (z = −2) shows clusters in bilateral ventral prefrontal cortices, left temporal lobe and left insular cortex. Middle panel (z = 22) shows clusters in bilateral dorsal prefrontal cortices. Right panel (z = 34) shows the cluster in ACC.

DO structures ("DO-only"), some only in PO structures ("PO-only"), and others equally in both ("Equal-DO-PO"). Subsequently, they watched and described new transfer actions on their own. On each trial, they were provided with the verb to use but were otherwise free to formulate the sentence in any way they chose. I examined neural activity during DO versus PO production, and the relationship between neural activity and behavioral output.

Participants were scanned between 1 and 3 days after training.[1] In addition to language production, they completed the Stroop and Number-Letter tasks. The former is a well-known measure of the ability to override a prepotent representation and choose an alternative. The latter indexes a different executive function called task-switching (Miyake & Friedman, 2012). The contrast between the two tasks helped determine if activation within a region of interest (ROI) was specific to conflict control or was applicable to any difficult executive function task.

I conducted whole-brain, ROI, and psychophysiological interaction (PPI) analyses aimed at answering two main questions: (1) Does neural activity during sentence production vary depending on individual differences in conflict control? (2) Is the neural activity associated with conflict control during speech sensitive to statistical properties of language exposure? Given the focus on conflict control, trials where speakers produced the less preferred DO structure after producing a PO on the previous trial were of particular interest. As mentioned above, this scenario requires overriding a preferred and primed structure and is therefore tailor-made for examining the role of conflict control in sentence production.[2] Multiple previous studies have identified the anterior cingulate cortex (ACC) as an important neural substrate for conflict control (Botvinick, Cohen, & Carter, 2004; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). The results demonstrate a role for this region in sentence choice, and provide broader insights into how the adult human brain adjusts to language input and uses different neural resources to accomplish the same speech goal.

2. Results

2.1. Behavioral results

Participants produced an average of 43% DO, 52.9% PO and 4.1% other structures. As predicted, the proportion of DO structures was significantly below 50%, indicating a dispreference for this structure ($t(24) = -3.05$, $p < .01$). Considering only the critical structures (DO and PO), proportion of DO produced in different exposure conditions was 45.2% (DO-only), 46.6% (Equal-DO-PO) and 42.5% (PO-only). Thus, participants produced numerically more DO structures with verbs that were associated with that structure during training (DO-only and Equal-DO-PO versus PO-only). However, mixed-effects analysis did not reveal any significant polynomial trends across exposure types (Linear: $z = -1.02$, Quadratic: $z = -1.29$, $ps > .1$). This could be due to insufficient power compared to a closely related behavioral study, which contained 88 participants and reported comparable DO production (Thothathiri et al., 2017: DO-only = 46.3%, Equal-DO-PO = 42.4%, PO-only = 41.9%).

2.2. fMRI results

Sentence production versus baseline revealed activation in lateral frontal, motor, temporal and visual cortices as well as medial regions including the supplementary motor area and the ACC (see Supplementary Fig. S1). My main analysis sought to identify brain regions where activation for producing DO after a previous PO correlated with individual differences in conflict control. This revealed significant positive correlations in medial and left frontal regions that are routinely associated with conflict control and language, including the ACC, the left dorsal prefrontal cortex and the left ventral prefrontal cortex (Fig. 1. See Supplementary Table S1). Individuals with better conflict control activated these regions more than those with poorer conflict control when producing a DO after a PO.[3]

Among the identified regions, activation during DO production (after a previous PO) overlapped with activation during Stroop in the ACC only (Fig. 2A). Therefore, I investigated this ROI further in more fine-grained analyses. First, I explored whether this ROI was specifically involved in Stroop-specific processes or whether it was involved in broader executive functions that could be shared with the Number-Letter task. This analysis revealed significant activation in the ROI during the Stroop task (Mean contrast estimate = 14.71, 95% CI = [0.14 29.29], $t(22) = 2.09$, $p < .05$) but not the Number-Letter task (Mean contrast estimate = −5.34, 95% CI = [−29.25 18.57], $t(22) = -.46$, $p > .6$). Activation for Stroop was significantly higher than that for Number-Letter (Mean of the difference = 20.06, $t(22) = 1.81$, one-tailed $p < .05$.[4] See Fig. 2B). Second, I asked whether recruitment of the ACC ROI was sensitive to language exposure.

[1] Fourteen participants returned for the scan the day after training; eleven others after more than a day. Time delay between training and scan did not significantly modulate the behavioral pattern (section 2.1) or the activation pattern in the anterior cingulate cortex (Fig. 2C). Therefore, this factor is not discussed further below.

[2] In contrast, producing DO after a previous DO should be easier due to priming. As expected, this analysis did not reveal any effects and is therefore not discussed.

[3] Analysis of negative correlation (higher activation by individuals with poorer conflict control) did not reveal any significant effects.

[4] My hypothesis is clearly directional (Stroop > Number-Letter and not the reverse). Further, I already conducted separate analyses for Stroop and Number-Letter and found that there was significant activation in the ACC ROI for the former but not the latter. Under these conditions, a directional one-tailed test is more appropriate than a non-directional two-tailed test because the reverse direction (Number-Letter > Stroop) is neither theoretically hypothesized nor empirically possible given the already observed results. For discussion of when a one-tailed test is warranted, see, for example, Cho & Abe (2013).