Journal Club

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Bilingual Language Control Mechanisms in Anterior Cingulate Cortex and Dorsolateral Prefrontal Cortex: A Developmental Perspective

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Review of Blanco-Elorrieta and Pylkkänen

Bilingual individuals purportedly outperform monolingual individuals in nonverbal tasks of executive function, such as the Simon, Flanker, and Stroop tasks (Donnelly et al., 2015). They are also less affected by age-associated cognitive decline (Bak et al., 2014). Hence, understanding the implications of learning a second language may teach us something about functional plasticity and far transfer effects, as well as inform educational policy and social practices. Yet the neurocognitive mechanisms behind the bilingual advantage remain mysterious. This, combined with inconsistent behavioral results, makes many cognitive neuroscientists question whether the reported bilingual advantage is real and not merely an artifact of particular research practices or publication bias (de Bruin et al., 2015; Paap et al., 2015).

The most commonly cited explanation for the bilingual advantage is the proposal by Green (1998) that managing two languages during language production constantly draws upon, and thus strengthens, domain-general (i.e., not language specific) executive control processes (e.g., conflict monitoring, interference suppression, selective response inhibition; Abutalebi and Green, 2016) that select words in the intended language while inhibiting the activation of words in the unintended language. The reason that production (rather than comprehension) is key is that bilingual individuals need to inhibit words in one language to generate words in the other, but they do not need to inhibit the activation of words in one language to understand words in another. Hence, according to Green (1998), the bilingual advantage stems from the frequent use of domain-general executive control processes in language production. Specifically, bilingual individuals regularly activate a network involving left inferior frontal gyrus (IFG) and dorsolateral prefrontal cortex (DLPFC) to inhibit and select between languages (Abutalebi and Green, 2016).

Although studies have demonstrated that bilingualism is associated with functional brain reorganization in children (Arredondo et al., 2016) and adults (Berken et al., 2016), no study had demonstrated that switching languages in production and not comprehension draws upon domain-general executive control processes until the Blanco-Elorrieta and Pylkkänen (2016) study. The significance of this particular study is that it provides crucial neurophysiological evidence in support of the theory by Green (1998) linking language switching in production with domain-general control processes, and language switching in comprehension with domain-specific (i.e., language) control processes. It did this by using magnetoencephalography (MEG) to measure, in a group of highly proficient Arabic-English bilinguals, the degree of overlap in neural activation between language-switching and category-switching tasks, during both language production (where participants were required to name target stimuli) and language comprehension (where they were instructed to match verbal and visual stimuli by pressing a button).

MEG data were analyzed from three different brain regions commonly implicated in language switching: DLPFC, left IFG, and left anterior cingulate cortex (ACC; Abutalebi and Green, 2016). Similar neural activation patterns were found in DLPFC during language-switching and category-switching tasks when the participants had to produce language but not when they had to merely understand language. In the latter (language comprehension) conditions, left ACC was selectively activated during the language-switching task. The effects of switching languages did not extend to left IFG, even though this region has been implicated in inhibitory control (Abutalebi and Green, 2016). However, this may have been because left IFG is also activated during language processing (Hagoort, 2005), and every experimental trial involved verbal

Received March 9, 2016; revised April 11, 2016; accepted April 15, 2016.

D.D. is supported by Grant RPG-2015-024 from The Leverhulme Trust. We thank Maria Arredondo (University of Michigan, Ann Arbor, MI) for her input.

The authors declare no competing financial interests.

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DOI:10.1523/JNEUROSCI.0798-16.2016

 0270-6474/16/365434-03$15.00/0

stimuli. Importantly, Abutalebi et al. (2012) and others have suggested that language switching in comprehension strengthens or adjusts a domain-general control mechanism in ACC, but the data from the study by Blanco-Elorrieta and Pylkkänen (2016) suggest that the control mechanism in ACC is language specific not domain general. Therefore, their data dovetail with the proposal by Green (1998) that managing two or more languages during production frequently recruits a domain-general executive control resource, leading to a bilingual advantage.

If the interpretation of the data from Blanco-Elorrieta and Pylkkänen (2016) is correct, then the bilingual advantage may arise from the experience of language production but not of language comprehension. However, the participants in the study by Blanco-Elorrieta and Pylkkänen (2016) were well rehearsed at both comprehending and producing two languages. To ascertain whether production rather than comprehension results in a bilingual advantage, one would ideally test for a bilingual advantage in people who can comprehend but not produce language. Fortunately, such people exist: preverbal human infants. Human infants learn to comprehend languages well before they are able to produce them (Bergelson and Swingley, 2012). Applying the theory by Green (1998) and interpretation of their own data by Blanco-Elorrieta and Pylkkänen (2016), preverbal infants who are exposed to a bilingual environment should not show any bilingual advantage. Yet, studies suggest that they actually do. For example, Kovács and Mehler (2009) used an eye tracker to measure the anticipatory looks of 7-month-old infants who were raised from birth in either a monolingual or a bilingual environment. All infants learned to associate a cue with a reward presented on one side of a screen. However, only bilingual infants were able to update their anticipatory looks when the cue began signaling the reward on the opposite side of the screen. How can this be reconciled with the neurophysiological data and theory? If the bilingual advantage arises as a result of language production, how can mere exposure to a bilingual environment confer cognitive benefits?

It is possible that, because every child adapts to his or her environment, exposure to varied, unpredictable language input (hearing two or more languages) leads to experience-driven adaptations that constrain brain and cognitive development. There are broadly two ways—consistent with the data from Blanco-Elorrieta and Pylkkänen (2016)—in which early experience-driven adaptations could give rise to a bilingual advantage. First, it is possible that to monitor multiple languages, preverbal infants draw upon neural resources in dorsal ACC (dACC) that are initially domain general, but which become gradually more specialized to language over developmental time. In other words, some neurons in dorsal ACC may initially be involved in a range of functions, but during ontogenesis their response properties become more specialized for language than neurons in DLPFC. ACC is indeed structurally and functionally heterogeneous, and its structures and functions change over developmental time (Wang et al., 2015). Furthermore, tasks that require adaptive control depend on two distinct frontoparietal and cingulo-opercular networks in the adult brain (the former, involving DLPFC, underpins highly adaptive control processes, and the latter, involving dACC, maintains tonic alertness; Coste and Kleinschmidt, 2016), but these two networks are less differentiated in children than in adults (Fair et al., 2007). Moreover, the dACC is actually part of the frontoparietal network in children. Over developmental time, it disconnects from the frontoparietal network and gradually becomes embedded in the cingulo-opercular network (Fair et al., 2007). This supports our suggestion that ACC may have contributed to domain-general executive control processes more in early than late development. However, we can only speculate as to why ACC would specialize more than DLPFC.

Second, it is possible that the inhibitory control mechanism of Green (1998) is just one of several mechanisms underpinning the bilingual advantage, and that these mechanisms have differential effects over the lifespan. For example, Donnelly et al. (2015) performed a meta-analysis of 73 studies that compared monolingual and bilingual individuals on tasks that contain trials with and without distracting information (e.g., Flanker, Simon, and Stroop tasks). The difference in reaction time (RT) between these two trial types is assumed to reflect the additional time needed to engage a domain-general inhibitory mechanism that suppresses distracting information. Donnelly et al. (2015) found that, whereas bilingual adults show more of an inhibitory control advantage (i.e., a smaller difference in RTs between the two trial types), bilingual children tend to show more of a general executive control advantage (i.e., a shorter average RT across both trial types). But what other mechanisms (besides inhibitory control) might give rise to a bilingual advantage? We know that postnatal auditory preferences are adaptively shaped by prenatal auditory learning experiences (Byers-Heinlein et al., 2010), and that perinatal learning involves the following two mechanisms: habituation and novelty preference. It is possible that exposure to bilingual input sharpens these perinatal learning mechanisms, which lead to cognitive benefits. How would this happen? Habituation is an adaptive process by which the infant orients to, and builds a model of, a familiar stimulus (e.g., maternal language). Infants who are exposed to more varied, less predictable language input may need to process information more efficiently, perhaps by learning to construct, and get by on, less detailed models, so they can orient sooner to less familiar (but equally important) stimuli (e.g., a second language). If this were the case, then we would expect "bilingual exposure" infants to show less familiarity preference and more novelty preference than their monolingual peers. This is indeed what happens in 4-month-old bilingual infants (Bosch and Sebastian-Galles, 1997). Furthermore, a recent article (Singh et al., 2015) found that 6-month-old bilingual infants habituate faster (i.e., build models quicker or construct less detailed models) than monolingual control subjects. Moreover, if bilingual infants have learned to get by on less complete internal models, it would explain why a recent study (Folke et al., 2016) found a bilingual disadvantage in metacognition, the ability to evaluate one's own cognitive processes. In other words, the language comprehension–production distinction in the study by Blanco-Elorrieta and Pylkkänen (2016) may explain some, but not all, bilingual advantage effects. To explain them all, it may be important to take into account developmental (context-dependent) adaptive processes.

In summary, bilingual individuals purportedly outperform monolingual individuals in nonverbal tasks of executive function and show slower rates of age-associated cognitive decline. Yet, the neurocognitive mechanisms that underlie the bilingual advantage remain controversial. An influential idea that is implicitly assumed in most contemporary bilingual advantage theories yokes language control (typically in production) to domain-general executive control mechanisms that are commonly localized in prefrontal cortex (e.g., in DLPFC). The study by Blanco-Elorrieta and Pylkkänen (2016) provides compelling evidence in support of this idea. However, neither the idea nor their data explain why a bilingual advantage is found in preverbal infants. Therefore, we suggest that the domain-general (inhibitory) control mechanism in DLPFC may be merely one of several mechanisms underlying the bilingual advantage, and that these may have differential effects across the lifespan. A developmental approach would be needed to elucidate them.

References

Abutalebi J, Green DW (2016) Neuroimaging of language control in bilinguals: neural adaptation and reserve. Biling Lang Cogn. Advance online publication. Retrieved April 22, 2016. doi:10.1017/S1366728916000225. CrossRef

Abutalebi J, Della Rosa PA, Green DW, Hernandez M, Scifo P, Keim R, Cappa SF, Costa A (2012) Bilingualism tunes the anterior cingulate cortex for conflict monitoring. Cereb Cortex 22:2076–2086. CrossRef

Arredondo MM, Hu XS, Satterfield T, Kovelman I (2016) Bilingualism alters children's frontal lobe functioning for attentional control. Dev Sci. Advance online publication. Retrieved April 21, 2016. doi:10.1111/desc.12377. CrossRef Medline

Bak TH, Nissan JJ, Allerhand MM, Deary IJ (2014) Does bilingualism influence cognitive aging? Ann Neurol 75:959–963. CrossRef

Bergelson E, Swingley D (2012) At 6–9 months, human infants know the meanings of many common nouns. Proc Natl Acad Sci U S A 109:3253–3258. CrossRef

Berken JA, Chai X, Chen J-K, Gracco VL, Klein D (2016) Effects of early and late bilingualism on resting-state functional connectivity. J Neurosci 36:1165–1172. CrossRef

Blanco-Elorrieta E, Pylkkänen L (2016) Bilingual language control in perception versus action: MEG reveals comprehension control mechanisms in anterior cingulate cortex and domain-general control of production in dorsolateral prefrontal cortex. J Neurosci 36: 290–301. CrossRef

Bosch L, Sebastián-Gallés N (1997) Native-language recognition abilities in 4-month-old infants from monolingual and bilingual environments. Cognition 65:33–69. CrossRef

Byers-Heinlein K, Burns TC, Werker JF (2010) The roots of bilingualism in newborns. Psychol Sci 21:343–348. CrossRef

Coste CP, Kleinschmidt A (2016) Cingulo-opercular network activity maintains alertness. Neuroimage 128:264–272. CrossRef

de Bruin A, Treccani B, Della Sala S (2015) Cognitive advantage in bilingualism an example of publication bias? Psychol Sci 26: 99–107. CrossRef

Donnelly S, Brooks PJ, Homer B (2015) Examining the bilingual advantage on conflict resolution tasks: a meta-analysis. Paper presented at the 37th Annual Conference of the Cognitive Science Society, Pasadena, CA, July.

Fair DA, Dosenbach NU, Church JA, Cohen AL, Brahmbhatt S, Miezin FM, Barch DM, Raichle ME, Petersen SE, Schlaggar BL (2007) Development of distinct control networks through segregation and integration. Proc Natl Acad Sci U S A 104:13507–13512. CrossRef

Folke T, Ouzia J, Bright P, De Martino B, Filippi R (2016) A bilingual disadvantage in metacognitive processing. Cognition 150:119–132. CrossRef

Green DW (1998) Mental control of the bilingual lexico-semantic system. Biling Lang Cogn 1:67–81. CrossRef

Hagoort P (2005) On Broca, brain, and binding: a new framework. Trends Cogn Neurosci 9: 416–423. CrossRef

Kovács ÁM, Mehler J (2009) Cognitive gains in 7-month-old bilingual infants. Proc Natl Acad Sci U S A 106:6556–6560. CrossRef

Paap KR, Johnson HA, Sawi O (2015) Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. Cortex 69:265–278. CrossRef

Singh L, Fu CS, Rahman AA, Hameed WB, Sanmugam S, Agarwal P, Jiang B, Chong YS, Meaney MJ, Rifkin-Graboi A (2015) Back to basics: a bilingual advantage in infant visual habituation. Child Dev 86:294–302. CrossRef

Wang J, Yang N, Liao W, Zhang H, Yan CG, Zang YF, Zuo XN (2015) Dorsal anterior cingulate cortex in typically developing children: laterality analysis. Dev Cogn Neurosci 15: 117–129. CrossRef