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Effect of monolingualism and bilingualism in the anterior cingulate cortex: a proton magnetic resonance spectroscopy study in two centers

Efeito do monolinguismo e do bilinguismo no córtex anterior cingulado: um estudo de espectroscopia de ressonância magnética de prótons em dois centros

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Abstract: Reports of an advantage of bilingualism on brain structure in young adult participants are inconsistent. Abutalebi et al. (2012) reported more efficient monitoring of conflict during the Flanker task in young bilinguals compared to young monolingual speakers. The present study compared young adult (mean age = 24) Cantonese-English bilinguals in Hong Kong and young adult monolingual speakers. We expected (a) differences in metabolites in neural tissue to result from bilingual experience, as measured by 1H-MRS at 3T, (b) correlations between metabolic levels and Flanker conflict and interference effects (c) different associations in bilingual and monolingual speakers. We found evidence of metabolic differences in the ACC due to bilingualism, specifically in metabolites Cho, Cr, Glx and NAA. However, we found no significant correlations between metabolic levels and conflict and interference effects and no significant evidence of differential relationships between bilingual and monolingual speakers. Furthermore, we found no evidence of significant differences in the mean size of conflict and interference effects between groups i.e. no bilingual advantage. Lower levels of Cho, Cr, Glx and NAA in bilingual adults compared to monolingual adults suggest that the brains of bilinguals develop greater adaptive control during conflict monitoring because of their extensive bilingual experience.
Keywords: H-MRS; Aging; Multilingualism; Flanker task; ACC; Cognitive control

Resumo: Relatos de uma vantagem do bilinguismo na estrutura cerebral em jovens participantes adultos são inconsistentes. Abutalebi et al. (2012) relataram uma monitorização mais eficiente do conflito durante a tarefa de Flanker em jovens bilíngues comparados com jovens monolíngues. O presente trabalho comparou jovem adultos (idade média = 24) bilíngues em Cantonês-Inglês de Hong Kong e jovens monolíngues adultos. Estávamos a contar com (a) diferenças em metabólitos no tecido neural como resultado de uma experiência bilíngue, medido pelo 3T 1H-MRS, (b) correlações entre os níveis metabólicos, conflito Flanker e efeitos de interferência (c) diferentes associações em falantes monolíngues e bilíngues. Encontramos evidências de diferenças metabólicas no ACC devido ao bilinguismo, especificamente nos metabólitos Cho, Cr, Gly e NAA. Porém, não constatamos correlações significativas entre os níveis metabólicos e efeitos de conflito e interferência e nenhuma evidência significativa de relações diferenciais entre falantes monolíngues e bilíngues. Além disso, não encontramos nenhuma evidência de diferenças significativas no tamanho médio dos efeitos do conflito e interferência entre os grupos, ou seja, nenhuma vantagem bilíngue. Níveis inferiores de Cho, Cr, Gly em adultos bilíngues em comparação com adultos monolíngues sugerem que o cérebro dos bilíngues desenvolve maior controle adaptativo durante a monitorização do conflito por causa da sua extensa experiência bilíngue.
Palavras-chave: H-MRS; Envelhecimento; Multilinguismo; Tarefa Flanker; ACC; Controle cognitivo

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Bilingualism is claimed to generate a significant positive influence on brain and cognitive functions. However, the neuro-cognitive benefits of bilingualism in young adults are inconsistent and therefore controversial in the literature (VALIAN, 2014). Studies show a global reaction time (RT) advantage on tasks requiring attention and executive control but these data are subject to criticism (e.g. VON BASTIAN; SOUZA; GADE, 2016). A bilingual advantage is reported on the Flanker task (ABUTALEBI et al., 2012), Simon task (BIALYSTOK; CRAIK; KLEIN; VISWANATHAN, 2004) and Stroop task (BIALYSTOK; CRAIK; LUK, 2008), as well as the Attentional Network Test (ANT) (ESTÉVEZ; CASTILLO, 2014). Reports of a behavioural bilingual advantage for young adults vary across studies according to differential task demands (PAAP; JOHNSON; SAWI, 2015), leading to debate over the specific conditions that lead to the bilingual advantage in young adults (ZHOU; KROTT, 2016; PAAP et al., 2015; VALIAN, 2015).

A bilingual advantage for young adults is seen in an RT advantage on the ANT and Flanker task. These tasks require participants to respond to the direction of a central arrow (left or right) flanked on either side by other arrows that are either pointing in the congruent (→→→→) or incongruent direction (←← → ←) or by two straight lines (-- -- → -- --) i.e. neutral flanker. This task yields two effects: interference (incongruent minus neutral) and conflict (incongruent minus congruent). Bilingual speakers show an advantage in both effects i.e. a reduced interference effect and a reduced conflict effect. Abutalebi et al. (2012) reported reduced RTs for a group of young bilinguals of the Flanker task that was correlated with decreased activation in the dorsal anterior cingulate cortex (ACC), suggesting more efficient engagement of ACC in monitoring nonlinguistic cognitive conflicts. This claim is consistent with studies showing that the ACC monitors conflict on Flanker trials (FAN et al., 2005). Monitoring conflict of a Flanker task trial is assumed to enhance cognitive control on subsequent trials, which is necessary to perform the task accurately. The ACC is assumed to play a role in models of cognitive control at the neural level. According to the conflict monitoring hypothesis (BOTVINICK; BRAVER; BARCH; CARTER; COHEN, 2001; BOTVINICK; COHEN; CARTER, 2004), cognitive control can be monitored by the dorsal ACC (dACC) whereas cognitive conflict is resolved via interactions between frontal, parietal and subcortical structures (NEE; WAGER; JONIDES, 2007; NIENDAM et al., 2012; CIESLIK; MUELLER; EICKHOFF; LANGNER; EICKHOFF, 2015). Therefore, our primary hypothesis is that the dACC will be engaged on Flanker conflict trials.

Abutalebi et al. (2012) report evidence to support this hypothesis in young bilingual speakers. They found that average grey matter volume (GMV) in the ACC of young bilingual adults is correlated with Flanker task effects. The dorsal ACC (dACC) and pre-supplementary motor area (pre-SMA) are associated with conflict monitoring. Pre-SMA is also engaged when speech is initiated in language switching tasks (see LUK; GREEN; ABUTALEBI; GRADY, 2012). dACC/Pre-SMA activation is also observed in language selection tasks in young adult bilinguals (ABUTALEBI; BRAMBATI; ANNONI; MORO; CAPPA; PERANI, 2007; WANG; XUE; CHEN; XUE; DONG, 2007; ABUTALEBI; ANNONI; ZIMINE; PEGNA; SEGHIER; LEE-JAHNKE; CAPPA; KHATEB, 2008; ABUTALEBI, et al. 2012; GUO; LIU; MISRA; KROLL; 2011; HOSODA; HANAKAWA; NARIAI; OHNO; HONDA, 2012; BRANZI; DELLA ROSA; CANINI; COSTA; ABUTALEBI, 2016) and on tasks requiring cross-linguistic conflict resolution in bilinguals (RODRIGUEZ-FORNELLS; VAN DER LUGT; ROTTE; BRITTI; HEINZE; MUENTE, 2005; VAN HEUVEN; SCHRIEFERS; DIJKSTRA; HAGOORT; 2008). dACC is assumed to resolve cognitive conflicts in both linguistic and non-linguistic contexts (ABUTALEBI et al., 2012; BRANZI et al., 2015). It is not surprising therefore that young bilingual adults show dACC activation on Flanker tasks. However, it is not certain if young bilingual adults who show an advantage in cognitive control on the Flanker task show differences at a neural level in the ACC.

Abutalebi and Green (2008) argued that the dACC is a domain general mechanism used for both cognitive and language control. This is supported with neuroimaging data. A bilingual advantage in conflict monitoring (a non-Flanker task) is associated with neuroplasticity in the dACC (ABUTALEBI et al., 2012) as well as left prefrontal cortex (STEIN et al., 2012), inferior parietal lobule (IPL) (MECHELLI et al., 2004; DELLA ROSA et al., 2013), and left caudate nucleus (ZOU; DING; ABUTALEBI; SHU; PENG, 2012). All of these brain regions are necessary for domain general cognitive control. It is therefore expected that a bilingual advantage in young adult bilingual speakers will be associated with neuroplasticity in the dACC.

One problem with all reported studies of neuro-plasticity in young bilingual adults is that mechanisms linking bilingualism and GMV are not linked in microstructure including neuro-metabolites. Magnetic resonance spectroscopy (1H-MRS) is used to test neuro-metabolite correlates in dACC at the molecular level including choline, creatine, and N-acetyl-aspartate. In a study of Cantonese-English speaking bilingual seniors from Hong Kong, Chiu et al. (2014) report a significant positive correlation between age and average levels of choline, creatine, and N-acetyl-aspartate in the ACC and

PCC. Increases in metabolites indicate glial proliferation and/or neuronal hypertrophy. Alternatively, increased ACC metabolites may be a feature of bilingual experience. If so we would expect to see differences between bilingual young adults in Hong Kong and monolinguals in Milan in mean levels of metabolites in the ACC. The goal of this study is to test the prediction that there is a positive relationship between mean levels of metabolites in ACC and performance on the Flanker task. In a novel paradigm, we used 3T 1H-MRS to compare mean level of metabolites in the ACC in young bilingual and monolingual adults and Flanker task performance. We expect (a) differences in mean metabolites in ACC to result from bilingual language experience in younger Hong Kong adults; (b) positive correlations between mean levels of metabolites in ACC and Flanker conflict and interference effects; and (c) a stronger pattern of correlations for bilingual speakers than monolingual speakers.

Methods

Participants: 21 young bilingual subjects (mean age ± standard deviation = 24.19 ± 2.25 years; age range 16-30 years; education = 17.6 ± 1.55 years; range 15-20 years) were recruited from students in Hong Kong. All were bilingual Cantonese-English speakers. Participants with any history of neurological and psychiatric illness were excluded. Socio Economic Status (SES) was assessed via questionnaire (mean = 45.18 ± 5.49; range: 31-54). Written consent was obtained from all participants. The study was approved by the Human Research Ethics Committee of the University of Hong Kong. A matched group of 20 healthy young monolingual subjects (mean age = 24.40 ± 2.11 years; age range 20-28 years; mean education = 16.80 ± 1.61 years; range 15-20 years) were recruited from students in Milan. Participants with any history of neurological and psychiatric illness were excluded. Written consent was obtained from all participants. The study was approved by the Ethics Committee at the University of Vita-Salute San Raffaele. Mann-Whitney test found no differences in age (p=0.25) or education (p=.119) between bilingual and monolingual groups.

Second language measures

Knowledge of second language and linguistic background of bilingual participants were assessed on picture naming tasks [30 stimuli selected and matched from the Snodgrass and Vanderwart battery (SNODGRASS; VANDERWART, 1980)], yielding a score for L1 and L2 proficiency and a self-report measure on L2 age of acquisition (AoA L2). Demographic data of bilingual and monolinguals are shown in **Table 1**.

MR scanning

MR scans on bilingual participants were performed using a 3.0 T scanner (Achieva TX, Philips Healthcare, Netherlands). Sensitivity encoding SENSE-head-8-coil was used. A standardized axial T1W3D volumetric fast field echo (FFE) sequence was employed using the following parameters: repetition time TR/TE = 8.0/3.9 ms, voxel size = 1×1×1 mm^3, field of view = 230×183 mm^2, slices = 150, reconstruction matrix = 256, flip angle 8° and turbo field echo factor = 163. Images were acquired from T1W 3D FFE were employed for the positioning of single voxel spectroscopy (SVS) for proton magnetic resonance spectroscopy (^{1}H-MRS). Point resolved spectroscopy (PRESS) was used as a volume selection method for region-of-interest and excitation was used for water suppression. Scanning parameters are TR/TE = 2000/39 ms, number of signals averaged = 128, phase cycles = 16, spectral width = 2000 Hz with spectral resolution of 1.95 Hz per point, and free induction decay = 1024. For shimming, pencil-beam-auto was employed. SVS of size 2×2×2 cm^3 was placed in the dorsal ACC (**Figure 1**). The whole scan took approximately 20 min. Monolingual participants had MR scanning at C.E.R.M.A.C (Centro di Eccellenza Risonanza Magnetica ad Alto Campo) at University San Raffaele, Milan. The same scanner model and exam cards (T1W 3D FFE and ^{1}H-MRS) used to scan bilingual subjects in Hong Kong were employed to scan the monolingual subjects in Milan in order to enhance images comparability.

Behavioral task

Bilingual and monolingual participants were given the Flanker task under exactly the same conditions. They were instructed to indicate as quickly and accurately as possible whether a central arrow (target) pointed to the right or left by pressing one of two buttons on a pad (ABUTALEBI et al., 2012; 2014). Three conditions types were presented: congruent, incongruent, neutral. Accuracy and reaction time (RT) were recorded (see **Table 1**).

Data Analysis

^{1}H-MRS

^{1}H-MRS spectra were processed using QUEST (quantification based on quantum estimation) within jMRUI 4.0. Metabolites, i.e. choline (Cho), creatine (Cr), N-acetly-aspartate (NAA), myo-inositol (mI), and Glx [summation of glutamate (Glu) and glutamine (Gln)], were measured and quantified as in (CHIU et al., 2014) (see **Figure 1**).

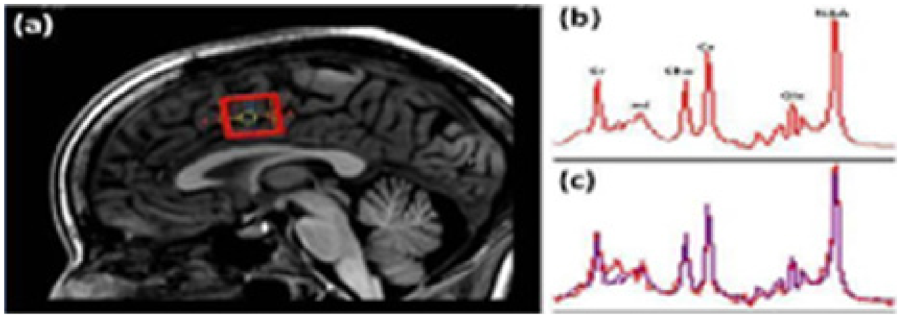

Figure 1. (a) Position of voxel placed in the dorsal anterior cingulate cortex; (b) simulated spectrum using the parameter QUEST in jMRUI; and (c) acquired spectrum (red) superimposed on the simulated spectrum (blue) from QUEST.

Image processing

To account for differences in water content in gray matter (GM), white matter (WM) and cerebrospinal fluid (CSF), we used voxel-based morphometry (VBM) to test the GM, WM and CSF composition within the SVS, as detailed in previous publications (CHIU et al., 2014, Mak et al., 2011). Furthermore, correction factors for T1 and T2 values were implemented (CHIU et al., 2014; MLYNARIK; GRUBER; MOSER, 2001).

Behavioral performance

Conflict effects (incongruent-congruent), interference effects (incongruent-neutral), and facilitation effects (congruent-neutral) were calculated and are summarised in **Table 1**.

Statistical Analysis

SPSS 20.0 was used for all statistical analyses. Mann-Whitney tests compared mean levels of metabolite concentrations and behavioral performance between bilingual and monolinguals. Also, the significance of relationships between mean metabolite concentration and behavioral performance was assessed via correlations (**Table 2**).

Table 1. Demographic data, mean metabolite concentrations, and mean behavioral performance of both bilingual and monolingual subjects.

Demographics	Mean		Nonparametric test (Mann-Whitney)
	Bilingual (n=21)	Monolingual (n=20)	p-value
Age (years)	24.19±2.25	24.40±2.11	0.250
Education (years)	17.60±1.55	16.80±1.61	0.119
SES	45.18±5.49	–	–
AOA L2	3.19±2.01	–	–
L1 NAM (hit %)	94.29±4.36	–	–
L2 NAM (hit %)	91.27±7.49	–	–
^{1}H-MRS (mM)			
Choline	2.22±0.39	2.39±0.23	0.025*
Creatine	13.63±1.84	14.00±3.06	0.006**
N-acetyl aspartate	10.91±1.79	12.00±0.76	<0.001**
Myo-inositol	6.23±1.79	6.00±3.33	0.419
Glutamate + Glutamine	14.66±1.87	15.13±1.42	0.045*
Behavioral performance (reaction time in milliseconds)			
Incongruent	589±73	591±65	0.814
Congruent	507±71	496±56	0.639
Neutral	496±66	490±51	0.896
Conflict effect	82±27	95±28	0.118
Interference effect	93±29	102±31	0.297
Facilitation effect	11±22	7±12	0.167

Key: AOA L2, age of second language acquisition; L1 NAM, first language naming; L2 NAM, second language naming; mM, millimolar; SES, Socioeconomic Status. *p<0.05, **p<0.01.

Table 2. Relationship between metabolite concentrations and behavioral performance of Flanker task in both bilingual and monolingual subjects.

	Choline		Creatine		N-acetyl aspartate		Myo-inositol		Glutamate + Glutamine	
	Bilingual	Monolingual	Bilingual	Monolingual	Bilingual	Monolingual	Bilingual	Monolingual	Bilingual	Monolingual
Incongruent	r=-0.11 p=0.962	r=0.239 p=0.311	r=0.013 p=0.957	r=-0.144 p=0.546	r=0.004 p=0.988	r=0.313 p=0.179	r=-0.127 p=0.584	r=-0.279 p=0.234	r=0.074 p=0.749	r=0.049 p=0.836
Congruent	r=0.031 p=0.893	r=0.125 p=0.600	r=0.070 p=0.762	r=-0.161 p=0.499	r=0.073 p=0.752	r=0.272 p=0.246	r=-0.047 p=0.839	r=-0.165 p=0.488	r=0.154 p=0.504	r=0.147 p=0.536
Neutral	r=0.029 p=0.900	r=0.154 p=0.518	r=0.070 p=0.763	r=-0.139 p=0.558	r=0.077 p=0.739	r=0.306 p=0.190	r=-0.118 p=0.612	r=-0.164 p=0.490	r=0.197 p=0.393	r=0.049 p=0.836
Conflict effect	r=-0.112 p=0.628	r=0.304 p=0.193	r=-0.151 p=0.514	r=-0.009 p=0.971	r=-0.183 p=0.428	r=0.178 p=0.453	r=-0.218 p=0.343	r=-0.316 p=0.175	r=-0.205 p=0.373	r=-0.184 p=0.438
Interference effect	r=-0.094 p=0.685	r=0.244 p=0.300	r=-0.127 p=0.583	r=-0.069 p=0.772	r=-0.167 p=0.471	r=0.147 p=0.535	r=-0.051 p=0.827	r=-0.310 p=0.183	r=-0.260 p=0.256	r=-0.056 p=0.815
Facilitation effect	r=0.013 p=0.955	r=-0.069 p=0.773	r=0.017 p=0.942	r=-0.156 p=0.511	r=0.004 p=0.987	r=-0.029 p=0.904	r=0.197 p=0.391	r=-0.072 p=0.763	r=-0.091 p=0.696	r=0.275 p=0.241

Key: r, Pearson correlation coefficient

Results

¹H-MRS

Mean metabolite concentrations for bilingual and monolingual participants are summarised in **Table 1**. Bilingual participants had significantly *lower* concentrations of Cho (p=0.025), Cr (p=0.006), NAA (p<0.001), and Glx (p=0.045), compared to monolinguals.

Behavioral

Mean behavioral results for Flanker task effects are summarised in **Table 1**. There were no significant differences in behavioral performance between the two groups.

Correlation between ¹H-MRS metabolites and behavioral performance

Relationships between mean metabolite concentrations and behavioral performance on the Flanker task for bilingual and monolingual participants are shown in **Table 2**. There were no significant relationships between mean metabolite concentration and behavioral performance (all p's>0.1).

Discussion

We expected (a) differences in mean metabolites in ACC to result from bilingual language experience in young Hong Kong adults; (b) positive correlations between mean levels of metabolites in ACC and Flanker conflict and interference effects; and (c) a stronger pattern of correlations for bilingual speakers than monolingual speakers. We found evidence of differences in mean metabolites in the ACC due to bilingual language experience in Cho, Cr, Glx and NAA (but not in mI). However, we found no significant correlations between the mean levels of metabolites in ACC and Flanker conflict and interference effects for bilingual speakers and monolingual speakers. Furthermore, we found no evidence of significant differences in mean size of the conflict and interference effects between groups i.e. no bilingual advantage. It is remarkable that differences in mean metabolites in the ACC were observed even when there is no bilingual advantage i.e. there is a dissociation between behavioural and neural effects of bilingual language experience.

Contrary to our prediction, mean levels of Cho, Cr, Glx and NAA were significantly *lower* in bilingual adults compared to monolingual adults. Age was correlated with mean levels of metabolites in Hong Kong seniors suggesting increased metabolites result from gliosis and neural atrophy. Out results do not challenge this hypothesis. However, our results do reveal a different pattern of brain metabolism for younger compared to older Hong Kong adults. We note that speculation on these differences requires a monolingual control group to determine whether mean metabolite levels result from aging or bilingual language experience. However, our results do resonate with other findings from studies of healthy young bilingual adults in other settings.

Abutalebi et al. (2012) reported fMRI and VBM analysis of high-proficient German L1 and Italian L2 bilinguals (mean age=23.35, SD±4.59) and Italian monolinguals (mean age=26.55, SD±4.15) correlated with Flanker task performance. In that study, bilinguals showed a significantly smaller conflict effect (RT advantage) in a second session of the experiment that was correlated with *reduced* activation in the dACC – from 77 voxels in the first session to 10 voxels in the second session (with faster RT). By contrast, monolinguals showed activation of 289 voxels in the first session, which *increased* to 297 voxels in the second session. Abutalebi et al. (2012) argued that bilinguals adapt to Flanker conflict effects better than monolinguals and lower dACC activation reflects the behavioural advantage in young bilingual speakers. We can compare our results to those of Abutalebi et al. (2012), as we used equivalent samples of monolingual controls (from Milan) and an identical (Flanker) task. Our results extend the findings of Abutalebi et al. (2012) to young Hong Kong bilinguals and we therefore contend that Hong Kong bilinguals adapt to conflict on the Flanker task better than monolinguals – at the neural level. Support for our conjecture in the behavioural data is not overwhelming. Although there is a trend toward significantly reduced conflict and interference effects for bilinguals compared to monolinguals, the group differences just failed to reach significance (p<.07). However, we submit that lower level of metabolites in dACC observed are compatible with adaptation to the conflict task. We do not believe that our effects are equivalent to Abutalebi et al. (2012) because the number of participants in our study was smaller and conflict and interference effects lacked power to attain the levels of significance. Furthermore, the neural advantage in the Abutalebi et al. study was mean GMV not mean level of metabolites. The relationship between GMV and metabolites in not well specified.

Abutalebi et al. (2012) report a behavioral-neurostructural analysis i.e. correlations between conflict effects and structural data reporting an inverse correlation between mean GMV in the ACC and the conflict effect. They suggested that greater GMV is associated with smaller conflict effects for bilingual *and* monolingual participants. Functional-structural analysis i.e. correlations between functional activity provided by BOLD signal and GMV also showed a positive correlation between mean GMV and blood flow in ACC. Furthermore, a regression analysis showed that mean GMV was a predictor of ACC activation in bilingual and not monolingual participants. We found lower levels of mean metabolites in ACC that we contend are the direct result of bilingual language experience but this was not significantly related to any form of behavioural advantage. To summarize, young adult bilinguals exhibit reduced levels of metabolites in ACC even if the behavioural effects are equivalent. This confirms the sensitivity of brain imaging data relative to behavioural data and speaks directly to the debate about the bilingual advantage (PAAP; GREENBERG, 2013; VALIAN, 2014).

Bilingual young adults are reported to show behavioural and cognitive advantages in inhibitory control and monitoring of attention which is manifest by a reduction in conflict effects and faster RT overall. However, the tasks used to test the bilingual advantage engage a number of cognitive process and they can be difficult to isolate (COSTA; HERNÁNDEZ; COSTA-FAIDELLA; SEBASTIÁN-GALLÉS, 2009; ONG; SEWELL; WEEKES; MCKAGUE; ABUTALEBI, 2017; ZHOU; KROTT, 2016). Paap and Greenberg (2013) point out that cognitive control subsumes executive processing (EP), which includes (1) setting of goals, (2) switching attention between goal-relevant information and (3) inhibiting irrelevant information. In our view, neural studies are more powerful.

There is no consensus regarding theoretical explanations for bilingual advantages. Two hypotheses are (1) the bilingual inhibitory control advantage (BICA) and (2) the conflict monitoring advantage (VON BASTIAN et al., 2016). The BICA hypothesis assumes that bilingual speakers recruit inhibitory control to manage cross-linguistic interference in language production (GREEN, 1998). BICA manifests when bilingual speakers must inhibit cross linguistic interference from competing languages and focus attention on target representations. As a result, it is assumed that bilinguals show more efficient inhibition on decision tasks requiring conflict resolution. One prediction that follows is more efficient inhibitory processing should be reflected in neural activity during the Flanker task (ABUTALEBI et al., 2014; COSTA et al., 2009). We found evidence of smaller interference effects for bilingual speakers although this was not significant due to sample size and lack of power. Reduced metabolites in bilingual speakers are assumed to result from efficient processing in the dACC. There is evidence of a bilingual behavioural advantage in young adults (COSTA et al., 2009) that is in turn a reflection of a domain general advantage in cognitive control. Our data show for the first time a neural advantage i.e. reduced levels of metabolite in bilinguals which we assume reflects the domain general advantage in cognitive control. Bilinguals are assumed to monitor language output routinely. Bilinguals can perform faster than monolingual speakers on Flanker trials because they can adjust to the changing demands across trials more efficiently (BIALYSTOK, 2006; COSTA et al., 2009; MARTIN-RHEE; BIALYSTOK, 2008). If a participant can adapt to Flanker trials more efficiently – requiring fewer trials – we might expect reduced metabolites as the number of trials increases. It was not possible to test this explanation directly because the derivation of metabolites required multiple observations across trials. However, our results confirm the expected correlation between faster RT and lower mean levels of metabolite for bilingual compared to monolingual speakers. We note that behavioural advantages are not universally observed for young bilingual adults (HILCHEY; KLEIN, 2011; PAAP; GREENBERG, 2013; PAAP et al., 2015). A coherent theoretical account of the bilingual advantage in young adults is still lacking and in our view requires reconciliation of the behavioral and brain data (PAAP et al., 2015).

Abutalebi et al. (2012) questioned whether bilingual advantages in young adults is specific to language learning or if skills are generalizable to other domains. They used an event-related (er-fMRI) design with VBM data, to test correlations between GM density, functional brain activation and behavioral performance. GMV in the ACC was positively correlated with functional activity (conflict monitoring on the Flanker task), and was stronger for bilingual than monolingual speakers. However, ACC activation was *lower* in bilinguals than monolinguals. We suggest that lower metabolic activity in the ACC observed here is also due to adaptation to a bilingual lifestyle in Hong Kong which requires regular, daily use of English and Mandarin as additional languages. In a similar study, Della Rosa et al. (2013) reported that mean GMV varies as a function of bilingual competence i.e. language proficiency reduced cognitive control. Our data converge with their data by revealing a cognitive control neural network in highly proficient non-native speakers of English that is derived from bilingual experience (see for review ABUTALEBI; GREEN, 2016). This includes the ACC, parietal lobe (IPL) and caudate nucleus (CN). We contend that the ACC is more efficient for young adult bilinguals in Hong Kong at a neural level specifically in neurotransmitter metabolism.

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