Brain Signal Complexity and Creative Ability in Bilingual and Monolingual Children

by

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A thesis submitted in conformity with the requirements for the degree of Master of Arts
Graduate Department of Psychology
University of Toronto

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Abstract

Childhood bilingualism has long been associated with enhanced creative performance. The neural mechanisms underlying this phenomenon, however, have yet to be characterized. Research suggests bilingualism modifies neural networks for executive control. Such changes, which can be assessed with estimation of neural signal complexity, are thought to increase information processing capacity. We thus compared electroencephalographic signal complexity during a Go/No-Go task in bilingual and monolingual children aged 4 to 6, and correlated these complexity estimates with creative ability. Differences in EEG complexity were found in left centro-parietal and right frontal scalp regions. Complexity, however, did not correlate with children’s creative performance scores. Although our findings failed to explain the neural link between bilingualism and enhanced creativity, we did find evidence to support the notion that bilingualism during early childhood is associated with functional brain changes in areas related to executive functioning.
Acknowledgments

The success of this project would not have been possible without the support and guidance of several individuals and institutions. First and foremost, to my advisor Sylvain Moreno, thank you for your wisdom, guidance, and patience over the past year. It was an honour to begin this long journey that is my postgraduate career with you. To Yunjo Lee, Patrick Bermudez, Lynn Williams and Natasha Kovacevic, I thank you for all your teachings and supervision throughout my data analysis. I also owe a debt of gratitude to Randy McIntosh and Cheryl Grady for being a part of my thesis committee, as well as to the funding agencies that supported my research. I am beyond grateful for having been given the opportunity to participate in this program and to work alongside such a highly esteemed group of individuals.

And to my family, thank you for being the best support crew I could have ever asked for.
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1 Introduction

The link between bilingualism and creativity has been the subject of much scientific inquiry over the past 40 years. Behavioural studies suggest that bilinguals are in general more creative than their monolingual counterparts (Ricciardelli, 1992b). What is perhaps most compelling is that this bilingual advantage is apparent in childhood, as evidenced by performance on verbal and nonverbal tests of divergent thinking (e.g. Garcia, 1996; Konaka, 1997; Stone, 1993). Studies employing these divergent thinking tests, widely believed to measure several facets of creative ability, have found that bilingual children display enhanced fluency (e.g. Carringer, 1974; Jacobs & Pierce, 1966; Ricciardelli, 1992a), flexibility (e.g., Carringer, 1974; Konaka, 1997), elaboration (e.g. Srivastava & Khatoon, 1980; Torrance, Gowan, Wu & Aliotti, 1970) and originality (e.g. Cummins & Gulutsan, 1974; Konaka, 1997; Okoh, 1980), as compared to monolingual children. Indeed, there is support that these childhood benefits persist throughout the lifespan (Getzels & Jackson, 1962; Karapetsas & Andreou, 1999; Kharkhurin, 2008, 2009, 2010a), underscoring the potential long-term advantages of childhood bilingualism on creative mentation. While there have been several behavioural findings to corroborate this bilingual advantage in children, no studies to date have examined the brain mechanisms underlying this phenomenon. Such an investigation would not only yield insights on the effects of bilingualism on cognitive and creative development, but may also elucidate the processes and mechanisms underlying creative cognition itself. Therefore, the impetus of the present investigation was to identify and characterize the neurobiological basis of enhanced bilingual creativity.

1.1 Executive control and bilingualism

It has been well established that the regular use of two languages during childhood (and at all ages, for that matter) bestows myriad advantages (Bialystok, 2001). Aside from the clear benefit of having a second language at one’s disposal with which to communicate, the bilingual experience appears to have a substantial impact on children’s cognitive functioning. This has been exemplified by numerous studies, wherein bilingual children have been shown to outperform their monolingual peers in various cognitive contexts, including the symbol-reorganization task (Peal & Lambert, 1962), the number concept task requiring participant to ignore misleading features (Bialystok & Codd, 1997), understanding object constancy (Feldman & Shen, 1971), and spatial problems (Bialystok & Majumder, 1998). Much work has shown that
in bilinguals the representational systems for both languages are simultaneously active in the mind and accessible when either language is being spoken (Bialystok & Craik, 2010). In order to resolve this conflict imposed by co-activation of languages, it is thought that executive functions – a group of general-purpose control mechanisms used to manage one’s thoughts and actions – are engaged during linguistic processing (Bialystok, 2011). Incidentally, this system is recruited during nonverbal tasks demanding selection or conflict resolution as well (e.g. Miyake et al., 2000). It is widely believed that continuous activation of this conflict management system during speech production results in its functional enhancement, leading to better executive control not only in language tasks but in non-linguistic tasks as well.

Of all the functions comprising the executive system, general consensus holds that bilingualism preferentially enhances inhibitory function, the capacity to inhibit inappropriate thoughts and behaviours, often in aid of selecting an appropriate alternative response (Bialystok, 2001; Green & Bavelier, 2008). Support for enhanced inhibitory control in bilingual children was first demonstrated by Bialystok (1999), who reported better bilingual performance on the dimensional change card sort task. This original finding has since been substantiated by further research employing varying methodologies (Bialystok & Martin, 2004; Bialystok & Viswanathan, 2009; Martin-Rhee & Bialystok, 2008). Neuroimaging studies are also revealing how the brain may bring about this cognitive plasticity in children. Clear language processing differences in the brain between bilingual and monolingual individuals have already been well documented (Abutalebi & Green, 2007). Indeed, mounting evidence suggests that bilingual language processing has the capacity to induce both structural (e.g. Luk, Bialystok, Craik, & Grady, 2011; Mechelli et al., 2004; Stein et al., 2012) and functional neuroplasticity (e.g. Bialystok et al., 2005; Gold, Kim, Johnson, Kryscio, & Smith, 2013). In children, research has shown bilingualism-related brain changes in linguistic processing (Rinker, Alku, Brosch, & Kiefer, 2010) and differences between monolinguals and bilinguals in white matter microstructure (Mohades et al. 2012). Recently, Barac, Moreno, and Bialystok (submitted) provided further support for bilingual brain plasticity, revealing evidence to corroborate enhanced cognitive inhibition in children. Using electroencephalography to record neuroelectric responses during a Go/No-Go task – used to assess children’s ability to inhibit a prepotent behavioural response – Barac and colleagues found functional brain differences in EEG components related to inhibitory control. Specifically, the researchers revealed shorter latencies for bilingual children on the N2
component in the frontal region, in addition to a larger P3 mean amplitude. These results, though preliminary, support the notion that better inhibition in bilingual children may be a consequence of bilingualism-induced plasticity in networks for inhibitory control.

1.2 Creativity

It is thus apparent that early childhood bilingualism leads to precocious development of cognitive abilities. This is underscored by the fact that bilingual children generally outperform their monolingual counterparts on diverse cognitive tasks. Interestingly, among the many cognitive advantages associated with bilingualism, none has puzzled researchers more than the observation that bilingual children also tend to surpass monolingual children on tasks of creativity.

Although several definitions of creativity have been put forward over the years, there is general consensus that creativity involves the ability to produce novel, original ideas or works that are both useful and appreciated by others (Sternberg & Lubart, 1996). Guilford (1967) proposed that this ability required initiating periods of convergent and divergent thinking in a cyclical fashion. Convergent thinking refers to a thought process used to come up with a single best answer to a problem; conversely, divergent thinking is a thought process invoked to generate multiple creative solutions. It was initially believed that both modes of thought differed in terms of attentional demand, where convergent thinking requires a high degree of attentional resources, while divergent thinking does not (e.g., Kasof, 1997), resulting in associative thought (e.g. Koestler, 1964; Mednick & Mednick, 1967; Ward, Smith & Vaid, 1997). Although some of these early views have since been refuted (see Dietrich, 2007), studies of divergent thinking have nonetheless remained the gold standard in creativity research. Guilford (1967) characterized divergent thinking according to four different traits: fluency, flexibility, elaboration and originality. Fluency refers to the capacity to generate a multitude of ideas; flexibility is described as the ability to evaluate several ideas at the same time; elaboration is viewed as the capacity to produce increasingly complex ideas from simpler ones; and originality is regarded as the ability to conceive ideas that deviate from the norm. Recent findings have shown that these traits can be combined to yield two types of creative functioning, the generative and innovative capacities (Kharkhurin & Samadpour Motalleebi, 2008; Kharkhurin, 2008, 2009). The generative capacity refers to the ability to conjure up and elaborate upon a large number of remote ideas. The
innovative capacity, on the other hand, is taken as the ability to generate both unique and appropriate ideas. This distinction is noteworthy given that it draws many parallels to Sternberg & Lubart's (1996) definition of creativity.

Although it has long been held that creative cognition relies upon the appropriate allocation of attentional resources, empirical research supporting this proposition is still lacking. Indeed, only a handful of studies to date have investigated the mechanisms of attentional control associated with creative task performance. Based on the extant literature, however, there seems to be some evidence that inhibitory processes may play a mediating role in creative ability (Dorfman, Martindale, Gassimova, & Vartanian, 2008; Vartanian, Martindale, & Kwiatkowski, 2007).

Though preliminary, these findings may begin to elucidate the higher creativity observed in bilingual children as compared to monolingual children. In fact, Kharkhurin (2011) recently demonstrated for the first time the potential mediating role of inhibitory function in adult bilingual creativity. By comparing moderately proficient bilinguals to highly proficiency bilinguals, Kharkhurin revealed not only higher inhibitory skill in the highly proficient bilingual group, but also a positive correlation between inhibitory function and creative performance within this group. Despite the absence of a monolingual group in this study, Kharkhurin’s findings nevertheless signal a potential relationship between enhanced inhibitory function and higher creative potential in bilingualism.

### 1.3 Brain signal complexity

If inhibitory control does in fact play a role in creative functioning in monolingual and bilingual speakers, it is a reasonable conjecture that the neurophysiological properties of the systems governing inhibition function might also be related to creative cognition and behaviour. Recently, there has been growing interest in studying moment-to-moment neural signal complexity, i.e. transient temporal fluctuations in the signal, as a means of studying information processing in the brain. It has become apparent that such fluctuations reveal considerable information about network dynamics that average brain activity alone cannot provide (Garrett, Kovacevic, McIntosh, & Grady, 2011; Vakorin, Lippé, & McIntosh, 2011). Computational work has established via neural network modeling that information integration across widely distributed neural networks is made possible by the spontaneous formation and dissolution of correlated activity between network nodes over time and across multiple timescales (Deco, Jirsa,
& McIntosh, 2011; Tononi, Edelman, & Sporns, 1998). It is these temporal dynamics of the brain’s functional connectivity that result in the fluctuations observed in the acquired brain signal (Breakspear, 2002; Freeman & Rogers, 2013; Friston, 2000; Honey, Kötter, Breakspear, & Sporns, 2007). It has been proposed that functional networks with more configurations have a greater capacity to dynamically explore and produce a more variable response (Deco et al., 2011; Ghosh, Rho, McIntosh, Kötter, & Jirsa, 2008; Tsuda, 2001). As such, signal complexity may be considered an index of the brain’s information processing capacity.

In a seminal empirical study by McIntosh, Kovacevic, & Itier (2008), complexity of single trial event-related potentials was assessed and related to performance on a face memory task in children and young adults. Counter-intuitively, complexity was found to increase rather than decrease with age. Furthermore, this increase in complexity correlated negatively with intrasubject reaction time variability and positively with performance accuracy. These results lent support to the notion that maturation leads to greater signal variability, and thus greater neural complexity. Indeed, during development, the brain becomes more differentiated and specialized; however, with this comes a concurrent increase in widespread structural and functional connectivity (Johnson, 2001). Therefore, as maturation progresses, the capacity of the system to invoke more simultaneous processes at any instant increases, resulting in more complexity in the brain’s activity (Friston, 1997). Critically, this complexity may be indicative of a greater range of metastable brain states and easier transitions between them, resulting in more stable behaviour. The authors further proposed that signal complexity might be used as a measure of the brain’s cognitive capacity.

1.4 Purpose and hypotheses

Based on the findings described above, we sought to use brain signal complexity as a means to investigate the neural mechanisms underlying creative performance in monolingual and bilingual children. To this end, we first set out to examine how early childhood bilingualism affects brain networks for inhibitory control. If bilingualism does indeed cause earlier development of executive control functions (Bialystok, 2001; Carlson & Meltzoff, 2008; Kovács & Mehler, 2009), we reasoned that these enhanced cognitive abilities, particularly inhibitory control, would be associated with greater complexity in corresponding brain networks. As such, we hypothesized that bilingual children would exhibit greater complexity in inhibitory networks.
than monolingual children. Next, given preliminary research suggesting the role of cognitive inhibition in creative performance (Dorfman et al., 2008; Stavridou & Furnham, 2006), we looked at whether inhibitory network complexity was related to higher creativity in bilingual relative to monolingual children. Our prediction was that greater inhibitory network complexity would be associated with better creative performance.
2 Methods

The data in the present study were collected by Barac et al. (submitted).

2.1 Participants

A total of 38 children aged 4 to 6 were recruited for this study. The sample consisted of 19 bilinguals (8 females) and 19 monolinguals (12 females) matched on non-verbal IQ, age, and socioeconomic status. Demographics are summarized in Table 1. Verbal consent was obtained from children; parents provided written consent. Approval for the study was granted by the York University Research Ethics Committee.

<table>
<thead>
<tr>
<th>Table 1</th>
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<tr>
<td>Demographic characteristics in monolingual and bilingual participants</td>
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</tr>
<tr>
<td>Age (month)</td>
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<tr>
<td>Home language child speaks*</td>
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<tr>
<td>Home language child listens*</td>
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<tr>
<td>Socioeconomic status</td>
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<tr>
<td>Estimated full-scale IQ</td>
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Values represent mean (SD)

Note: * indicates statistical significance ($p < .05$)

2.2 Background questionnaire

Parents filled out a background questionnaire (Appendix A). Information regarding their child’s languages spoken, language proficiency and age of language acquisition, in addition to the parent’s education, were gathered (see Table 1).

2.3 Test of creativity

Divergent thinking ability was assessed using the Thinking Creatively in Action and Movement (TCAM, Torrance, 1981). Preschool-aged children (aged three to eight years) have limited
capacities for expressing themselves through words or drawings. As such, rather than communicate their thoughts through these modalities, they prefer to express themselves kinaesthetically. The TCAM is thus appropriate as it relies on the kinaesthetic modality and does not require verbal responses, although verbal responses are permissible. The TCAM assesses aspects of divergent thinking – fluency, originality and imagination – through the following movement and manipulation activities:

- **Task 1:** “How Many Ways?” asks the child to come up with different ways to move across the floor
- **Task 2:** “Can You Move Like This?” has the child imitate the movements of an animal or a tree
- **Task 3:** “What Other Ways?” entails having the child conjure up various ways of placing a paper cup in a wastebasket
- **Task 4:** “What Might It Be?” requires the child to generate many uses for a paper cup

**Scoring.** Verbal and movements were recorded by the tester and rated according to the criteria outlined in the scoring guide. Performance on tasks 1, 3 and 4 were used to measure fluency and originality; task 2 was used to evaluate imagination. Fluency scores were calculated by tallying the pertinent responses on each task. Responses were assigned 0 to 3 points for their originality; this score was based on the statistical frequency of all responses. A 5-point Likert scale, which ranged from “no movement” to “excellent; like the thing”, was used to obtain an imagination score.

### 2.4 Stimuli and task procedure

Executive functioning was assessed using a Go/No-Go task where participants were instructed to signal (Go trials) the presence of white geometric shapes and to inhibit a response to purple geometric shapes (No-Go trials) (see Figure 1). The complete set of stimuli included the following: a white triangle, a purple triangle, a white square and a purple square. Two different shapes were used to circumvent potential repetition effects caused by identical color-shape pairing. Images were randomly presented to participants on a computer screen in the Go/No-Go protocol. Test blocks began with a prompt that provided instructions. For each trial, a black
background with a white cross at the center appeared on the screen for 500 to 1,000 ms. A shape was subsequently displayed for a maximum of 500 ms, followed by a post-stimulus interval of 500 ms. Participants were required to press a key on Go trials, and to withhold a response on No-Go trials. Feedback on performance was not provided. Accuracy rates were measured for both stimulus events; reaction times were recorded for Go trials only. A total of 200 stimuli were presented to the participants (80% Go trials and 20% No-Go trials), and the task lasted 15 min. Presentation of the stimuli was carried out using the Presentation software package (Presentation 12.00, Neurobehavioral Systems, U.S.A.).

**Figure 1.** Schematic diagram of trial structure and stimuli

### 2.5 EEG recording

Electroencephalography (EEG) is a non-invasive technique for recording electrical brain activity from the scalp. Brain wave patterns captured by EEG are the direct result of thousands to millions of neurons generating ionic current flows within and across cell assemblies. The EEG predominantly reflects voltage fluctuations induced by excitatory and inhibitory postsynaptic potentials from apical dendrites of a large number of similarly oriented, synchronized cortical neurons. Single-neuron electrical recordings from outside the head are unfeasible, for the
electrical output is far too faint to be detected. However, activity across myriad localized neurons overcomes this impediment, as simultaneous post-synaptic currents within neural ensembles amount to considerably larger currents. Such ionic currents have the capacity to traverse the conductive medium of the brain, reaching the skull, where EEG recording devices can detect it. Once picked up by electrodes along the scalp, these signals are amplified and subsequently stored in digital format on a computer. EEG is highly regarded for its ability to examine brain activity with high temporal resolution, on the order of milliseconds. This methodology, unfortunately, provides low spatial resolution. As such, brain electrical responses cannot be localized to specific anatomical structures and circuits. With a dense enough electrode array and sophisticated software, however, voltage patterns across the scalp may be ascribed to their electrical sources within the brain, although the reliableness of this technique is still highly questionable.

For the present study, EEG was continuously recorded while participants completed the Go/No-Go task. Recordings were obtained using a Biosemi amplifier system (BioSemi Active 2, Amsterdam) from 64 scalp electrodes embedded in a child-sized cap, placed in accordance with the international 10-20 system. A Common Mode electrode was used for on-line recording. To register eye movements and blinks, an electrooculogram (EOG) was measured from four additional electrodes, one located at each of the outer canthi and below each eye. The EEG signal was digitized at 512 Hz, and impedances were maintained below 20 µV.

2.6 EEG preprocessing

EEG recordings were pre-processed using the EEGLAB software (Delorme & Makeig, 2004). Data were digitally filtered with a 0.1 to 50 Hz bandpass filter. A subset of electrodes was excluded from the data analysis because of excessive artefacts (Fp1, Fpz, Fp2, T7, TP7, T8, TP8, Iz). Fifty-eight active electrodes remained for all participants. The continuous EEG was segmented into Go and No-Go (-200 to 1400 ms) stimuli events. Trials containing excessive amplitudes were removed, with amplitude threshold adjusted on a participant-by-participant basis to include a minimum of 80% target stimuli. Thresholds ranged from 300 to 400 µV. Further artefact removal was performed using independent component analysis (ICA). ICA decomposition was performed on the remaining concatenated trials. Each component was examined using its topography, power spectrum, and activity over time and trials. Components
carrying ocular artefacts were removed from the data set. The number of rejected ICA components was not statistically different between groups. Only correct trials were considered in the analyses. The number of trials contributing to MSE estimation for the bilingual children was 129.94 (SD = 17.70) for the Go trials and 32.44 (SD = 4.52) for the No-Go trials. Likewise, the number of trials contributing to MSE estimation for the monolingual children was 120 (SD = 15.72) for the Go trials and 29.56 (SD = 5.99) for the No-Go trials. There were no significant differences between the two language groups on either the number of Go or No-Go trials.

2.7 Multiscale entropy analysis

Multiscale entropy (MSE) was used to compute post-stimulus signal complexity at various timescales. The algorithms needed to calculate these entropy measures are provided online at www.physionet.org/physiotools/mse/. MSE analysis (Costa, Goldberger, & Peng, 2005) is a two-step process. First, the EEG time series undergoes coarse-graining (down-sampling), which generates several time series by averaging data points within non-overlapping windows of increasing length, \( \tau \). This coarse-graining process is done across both trial and condition. Individual elements comprising the coarse-grained time series, \( j \), are computed using the following equation (Equation 1):

\[
y_j^{(\tau)} = \frac{1}{\tau} \sum_{i=(j-1)\tau+1}^{j\tau} x_i
\]

(1)

\( \tau \) is also referred to as the scale factor. With this value, the length of a coarse-grained time series, \( N/\tau \), can be determined. The original time series constitutes the first timescale. In the second step of the MSE analysis, sample entropy (SE) (Richman & Moorman, 2000) is quantified for each scale. This measure provides an index for the appearance of repetitive patterns in the signal. The equation for performing this step is provided below (Equation 2):

\[
S_E(m, r, N) = \ln \frac{\sum_{i=1}^{N-m} n_i^m}{\sum_{i=1}^{N-m} n_i^{m+1}}.
\]

(2)

For a given time series, this formula computes the conditional probability that any two sequences of \( m + 1 \) data points will match provided the first \( m \) points match. Sample entropy is the natural
logarithm of this value and provides an index of the variability of the time series. In our study, the parameters \( m \) and \( r \) will be set to 2 and 0.5, respectively. That is, two consecutive data points will be used for pattern matching and data points will be treated as equal if the absolute difference between them is less than 50% of the time series standard deviation. A channel specific MSE estimate was obtained for each participant as a mean across trial entropy measures for scales 1 to 14. Sample entropy was not calculated for scales greater than 14, as the number of time points within the corresponding downsampled time series were insufficient (<50 time points) for reliable entropy estimation.

2.8 Statistical analysis

The behavioural data from the Go/No-Go task were examined with regards to reaction time (RT) on Go trials, accuracy (percent correct responses) on both conditions and sensitivity (d’). The measure of accuracy for Go and No-Go performance was defined, respectively, as the number of hits divided by the total number of Go stimuli and the number of correct rejections divided by the total number of No-Go stimuli expressed as a percentage. D-prime values were calculated as the difference between the z-transformation of the hit rate (correct “Go” response for “Go” items) and the z-transformation of the false alarm rate (incorrect “Go” response for “No-Go” items). Two-way mixed analyses of variance (ANOVAs) were performed separately for each behavioural measure, with language group as a between-participant factor and condition (Go and No-Go) as a repeated within-participant factor. A two-way mixed ANOVA was conducted on the TCAM scores, with language group as a between-participant factor and divergent thinking trait (fluency, imagination and originality) as a within-participant factor. Where sphericity assumptions were violated, probability estimates are based on Greenhouse-Geisser corrections.

Statistical assessment of language group and condition on MSE scores was conducted by partial least squares (PLS) (Krishnan, Williams, McIntosh, & Abdi, 2011; Lobaugh, West, & McIntosh, 2001; McIntosh, Bookstein, Haxby, & Grady, 1996). PLS is a multivariate statistical technique that identifies a set of latent variables (LVs) that account for maximum covariance between brain activity and experimental design (task PLS) or behavioural measurements (behaviour PLS). Task PLS was carried out on data matrices consisting of participant and channel specific measures. Participants by language group were designated to rows, and post-stimulus measures for MSE estimation by channel were assigned to columns. Matrices were then mean-centered within a
group. That is, in mean-centered task PLS, the task means are represented as the deviation around the grand mean (computed within each group) for each electrode and time point. The data are averaged within a condition and then these task means are averaged to obtain a grand mean. This grand mean is subtracted from the task means to obtain mean-centered values for each electrode and time point. The mean-centered matrices were decomposed with singular value decomposition (SVD) to identify the strongest condition differences and the corresponding scalp topography. This produced a set of orthogonal latent variables (LVs). Each LV comprises a “brain LV” (the brain portion of the LV) and a “design LV” (design portion of the LV). The brain LV denotes the weighted linear combination of electrode sites and time points that co-vary with the design LV pattern. Projecting the brain LV onto each participant’s EEG data by condition yields scalp scores, which can be positive or negative, depending on the relation between electrode/time and design LV. For behaviour PLS analyses, correlations were computed between the TCAM scores (fluency, originality, imagination) and MSE estimates across the entire sample.

Effect significance for the association between task conditions and brain response across language groups (task PLS), and between brain and behaviour performance (behaviour PLS), were determined using permutation tests (500). Using 500 bootstrap samples, bootstrap estimation of confidence intervals was used to assess the accuracy of the scalp topographies. Bootstrap ratios were subsequently obtained by dividing singular vector weights for each channel by bootstrap estimated standard error.

Univariate analyses were used to further probe group differences in MSE. To that end, we selected and clustered electrodes at which the contrast across conditions was most stable, as determined by bootstrapping, following task PLS. Mixed ANOVAs were conducted at these sites to evaluate localized MSE differences between groups for each task condition. Group (2 levels; bilingual, monolingual) was the between-subjects factor while temporal scale (3 levels; 1, 7, 14) served as the within-subjects factor. Greenhouse-Geisser corrections were used where sphericity assumptions were violated. Multiple pairwise comparisons were adjusted with Bonferroni corrections to control Type 1 error inflation.
3 Results

3.1 Behavioural performance: Effects of bilingualism on executive and creativity performance

Behavioural findings are summarized in Table 2. A one-way ANOVA revealed no significant group difference for reaction time on Go trials (F<1); however, it did find a near significant effect for d’ (F\textsubscript{1,37} = 3.72, p = 0.06) suggesting bilingual children’s better performance (Fig. 2). To investigate accuracy rates on the task, a two-way mixed measures ANOVA with group as a between-subjects factor and condition (Go, No-Go) as a within-subjects factor was carried out. There was a near significant main effect of group (F\textsubscript{1,36} = 3.72, p = 0.06), but no main effect of condition (F<1). There was no significant interaction (F<1) (Fig. 3). Bilingual children tend to score more accurately than monolingual children in both conditions.

Analysis of the TCAM scores revealed no group effect (F\textsubscript{1,36} = 2.06, p = 0.16), nor group x trait interaction (F\textsubscript{2,72} = 0.34, p = 0.72) (Fig. 4).

### Table 2

<table>
<thead>
<tr>
<th>Behavioural performance on Go/No-Go task by language group</th>
<th>Monolinguals (n = 19)</th>
<th>Bilinguals (n = 19)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage correct Go trials</td>
<td>75.66 (9.51)</td>
<td>80.76 (12.01)</td>
</tr>
<tr>
<td>RT mean go trials</td>
<td>658.04 (86.76)</td>
<td>636.73 (57.13)</td>
</tr>
<tr>
<td>Percentage correct No-Go trials</td>
<td>77.11 (14.05)</td>
<td>82.11 (12.62)</td>
</tr>
<tr>
<td>Discriminability index (d’)</td>
<td>1.58 (0.57)</td>
<td>2.05 (0.89)</td>
</tr>
</tbody>
</table>

Values represent mean (SD)

Note: * indicates statistical significance (p < .05)

3.2 Task PLS results: Effects of cognitive control on brain signal complexity

The task PLS analysis examined signal complexity across the whole scalp between the two task conditions across all participants. A single LV was significant with \( p = 0.004 \) (see Fig. 5). The topographic plot depicts the spatiotemporal distribution of this contrast. The spatial distribution
of the contrast was particularly stable at electrodes over right frontal and occipital regions for Go trials, and stable at electrodes over the left central parietal region for No-Go trials.

### 3.3 Task PLS results: Effects of bilingualism on brain signal complexity

The task PLS examined MSE between the two task conditions with two language groups. No LV was significant. One limitation of PLS is that it uses mean-centered values of each group (i.e., deviations from a grand mean within a group) and therefore may not be an optimal method to compare groups. Group differences were thus further explored by univariate analyses of MSE values in each condition, within left central parietal and right frontal regions where the contrast across conditions was most stable. To this end, we averaged MSE between electrodes C3 and CP3 (i.e., CP3/C3 cluster), and between F4 and F6 (i.e., F4/F6 cluster). MSE values are depicted across all temporal scales in **Figures 6 and 7**. A group x temporal scale ANOVA on the CP3/C3 cluster revealed that Go MSE was significantly higher in monolinguals \((F_{1,36} = 5.08, p = 0.03)\). A significant group x timescale interaction was also found \((F_{2,72} = 6.25, p = 0.003)\): the two groups showed similar MSE values in temporal scale 1 but differed in later scales. Indeed, post hoc tests revealed higher MSE at temporal scale 14 in monolinguals than in bilinguals \((p = 0.007)\).

Analysis of No-Go MSE found no group effect \((F_{1,36} = 2.78, p = 0.1)\), but did reveal a significant interaction between group and temporal scale \((F_{2,72} = 3.49, p = 0.04)\) suggesting that the groups showed different patterns of MSE across temporal scales. Post hoc analysis did not reveal any significance group differences.

A group x temporal scale ANOVA run on Go MSE data in the F4/F6 cluster showed no group effect \((F_{1,36} = 0.47, p = 0.5)\); however, it did reveal a significant group x temporal scale interaction \((F_{2,72} = 12.03, p < 0.001)\). Post hoc tests determined that MSE was higher for the bilingual group at temporal scale 1 \((p = 0.01)\), but higher for the monolingual group at temporal scale 14 \((p = 0.008)\). An ANOVA with No-Go MSE values revealed a similar pattern of results: a significant interaction \((F_{2,72} = 11.23, p < 0.001)\) but no group effect \((F_{1,36} = 0.14, p = 0.71)\). Post hoc analysis showed higher MSE at scale 1 for bilinguals \((p = 0.01)\) and higher MSE at scale 14 for monolinguals \((p = 0.01)\).
3.4 Behaviour PLS: Relationship between divergent thinking ability and brain signal complexity

The behavioural PLS analysis was first used to assess the relationship between divergent thinking ability and brain signal complexity across all participants. We correlated participants’ TCAM scores with their MSE values for both task conditions. No significant LVs were identified. Then, the behaviour PLS was run within each group separately; we failed to observe any significant relationships within either group.

Figure 2. Group mean d-prime scores with corresponding standard errors.
**Figure 3.** Group mean Go/No-Go task accuracy with corresponding standard errors.

**Figure 4.** Group mean TCAM trait scores with corresponding standard errors.
Figure 5. Contrasting the MSE response to Go vs. No-Go trials across all subjects. The bar graph depicts the contrast between the conditions, which was significantly expressed across the entire data set as determined by permutation tests and bootstrapping. The image plot highlights the electrodes at which the contrast across conditions was most stable as determined by bootstrapping. The head plot illustrates the spatial distribution for a representative timescale. Values represent ~z scores and negative values denote significance for the inverse condition effect. Red: Go trials; Blue: No-Go trials.
Figure 6. Group-related differences in multiscale entropy across temporal scale and task condition for channel cluster C3-CP3. Group means for MSE estimates are shown, along with corresponding standard errors.
Figure 7. Group-related differences in MSE across temporal scale and task condition for channel cluster F4-F6. Group means for MSE estimates are shown, along with corresponding standard errors.
4 Discussion

Bilingual and monolingual children completed a series of tasks measuring executive control, namely inhibitory function, and creative ability. Electrical brain activity recorded during the executive task was contrasted between both groups of children to test for differences in inhibitory network complexity. These complexity estimates were subsequently correlated with children’s creativity scores to assess the association between inhibitory network efficiency and creative output. The behavioural results (d’ and accuracy) from the go/no-go task found a marginal advantage of bilingualism in inhibitory control. Our results of signal complexity revealed differences between bilingual and monolingual children over localized regions of the scalp. These brain differences, however, were not found to be associated with the children’s performance on the creativity task. Each of these findings will be discussed in turn.

4.1 Executive and creativity performance

We assessed aspects of executive control in young bilingual and monolingual children with a Go/No-Go paradigm, in which children were required to withhold a habitual response to infrequent stimuli. In this way, we were able to investigate the putative effects of early bilingualism on executive functioning. The marginal main effect of language group on d’ showed a bilingual advantage on task performance, in that bilingual children had less difficulty in accurately identifying the task stimuli than monolingual children. Moreover, overall accuracy on the Go/No-Go task was marginally significantly higher in the bilingual children. Reaction time was no different between groups, however. Failure to reach statistical significance for the d’ and overall accuracy measures in particular may be accounted for by a few possibilities. First, lack of power may have precluded us from observing any significant differences in our sample. Secondly, the bilingual children’s language proficiency may not be high enough to have conferred any cognitive benefits (Cummins, 1976). Unfortunately, we did not have a proficiency measure to reconcile this issue. Alternatively, there is some literature showing that both monolingual and bilingual children are equally accurate at inhibiting a prepotent response (e.g. Bialystok & Martin, 2004; Martin-Rhee & Bialystok, 2008). Instead, it has been argued that superior bilingual cognitive performance is linked to enhanced interference suppression, another component of inhibitory control, which refers to the ability to ignore irrelevant information in favour of selecting a target. Subsequent research should make efforts to address these concerns.
Analysis of the children’s creative performance revealed that bilingual and monolingual children performed equivalently. This observation challenges our initial hypothesis, which predicted that the former group would exhibit higher creativity. One reason we may have failed to observe any significant differences in creative performance may again be related to levels of language proficiency in our bilingual sample. This interpretation is in line with results obtained by Ricciardelli (1992a), who found evidence to support a relationship between bilingual language proficiency and enhanced creativity in children. In comparing high- and low-proficient bilingual children with monolingual children, Ricciardelli noted higher creativity only in the high proficient group, compared to the monolingual group. This phenomenon has recently been observed in adult samples as well (Kharkhurin, 2010a, 2010b). Alternatively, we may not have observed a group difference because of the creative task we employed. It has been argued that many of the tasks currently in use mix both divergent and convergent processes, which may rely on different cognitive mechanisms (Hommel, Colzato, Fischer, & Christoffels, 2011). It is possible that the task we opted for, the TCAM, does not exclusively tap divergent thinking processes, as previous literature claims, thus obscuring a potential significant relationship between enhanced inhibitory function and better divergent thinking ability in bilingualism. Our inability to reproduce previous findings is not entirely unexpected, as Ricciardelli (1992a) found a number of studies that did not find divergent-thinking advantages in bilingual individuals. Presumably, varying results within the field are related to a lack of conceptual clarity as seen here, in addition to prodigious methodological and sample heterogeneity. Future research will no doubt need to refine current conceptionalizations of creativity and its measurement before the link between bilingualism and creativity can be reliably assessed, at least from a behavioural and cognitive perspective.

4.2 Brain signal complexity, bilingualism and creativity

Using multiscale entropy, we found a robust dissociable scalp topography between task conditions. Go trials were associated with greater MSE in right frontal and occipital leads; No-Go trials, with greater MSE in left centro-parietal leads. Furthermore, these contrast patterns were consistent across all timescales. Vakorin et al., (2011) recently showed a relationship between MSE timescale and local versus distributed information processing. Specifically, the researchers found that finer and coarser temporal scales were linked to local and distributed
information processing, respectively. Our findings thus suggest that Go and No-Go task demands increase information processing across both local and distributed regions.

An obvious drawback to our MSE data, however, lies in its low spatial resolution. Without running a source analysis, it is difficult to comment on the exact brain structures responsible for generating these scalp topographies. Drawing on studies of response inhibition using high-spatial resolution neuroimaging techniques, and work using source analyses with high-density electrophysiological data (e.g. Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Ciesielski, Harris, & Cofer, 2004), we hold that the neural signals obtained at these electrodes originate from nearby structures. In doing so, the topographies obtained from our analyses strongly suggest the involvement of executive control networks implicated in Go and No-Go performance. Higher MSE over right frontal and occipital regions may signify increased top-down attentional control of visual processing during Go trials. Interestingly, greater MSE in the No-Go condition was confined to an area over the left centro-parietal cortex, possibly indicative of functions related to attention shifting (Behrmann et al., 2004). This lends support to the proposition that No-Go related activity recruits more posterior regions during childhood, but with development, engages more frontal areas (Bunge et al., 2002). Source analyses of our own, however, will be required to fully substantiate these claims.

Our local analyses within left centro-parietal and right frontal scalp regions revealed significant group differences, although the patterns of results were not as we expected. In the centro-parietal region, Go-related complexity was higher in monolinguals than in bilinguals. We propose that this observation may still be related to precocious development of executive networks in bilingual children. As described above, development may bring with it more recruitment of frontal regions (Bunge et al., 2002); if bilingualism does indeed lead to faster brain development, lower complexity in the centro-parietal region in bilingual children may be related to the spreading of brain activity over a more distributed fronto-parietal network. Our complexity findings from the right frontal scalp region may also lend support to the notion of faster brain development as a result of early bilingualism. Although complexity was higher at the last temporal scale in monolinguals compared to bilinguals, the reverse was observed at the first temporal scale, whereby bilinguals were characterized by higher complexity. As described by Vakorin et al. (2011), greater complexity at finer temporal scales may be indicative of greater neural specialization.
Lastly, we did not manage to find any significant relationship between signal complexity in inhibitory networks and creative performance. As we noted previously, this may be due to the fact that bilinguals were not proficient enough in both their languages to have gained any cognitive advantage over their monolingual counterparts. Alternatively, if response inhibition is in fact not the mediating mechanisms underlying enhanced bilingual creativity, it follows that its corresponding brain activity would not be linked to creative performance either.

4.3 Conclusions and future directions

In the present study, we found brain complexity differences between bilingual and monolingual children in regions associated with executive control. These brain differences, however, were not related to enhanced creative performance. As an extension of this work, the same data set could be further analyzed using more traditional mean amplitude and spectral power approaches and subsequently correlated with our creativity scores. This may be instructive on account that these measures reflect properties of brain function different from those revealed by MSE. Future research aiming to characterize the link between bilingualism and creativity should consider language proficiency as well as the specific inhibitory control components (i.e. response inhibition vs. interference suppression) that may be affected by bilingualism. Further, it may be informative to record brain activity while bilingual and monolingual children engage in a creativity task, thus providing a more direct window into the brain dynamics linked to creative cognition. Doing so will provide a more comprehensive understanding of the effect of early bilingualism on the specific cognitive and neural mechanisms underlying creative ability.
References


Barac, R., Moreno, S., & Bialystok, E. (submitted) Developmental neuroplasticity in young bilingual children: Evidence from ERPs in a go/no-go task.


Appendix 1: Background questionnaire

Smarter Kids

Language and Social Background Questionnaire
To Be Completed by Parents

Today's date: __________________

Completed by: Mother   Father   Other _________

PART A:

The following information refers to the CHILD:

Participant ID: __________________

Date of birth (Day/Month/Year): __________________________ Gender: _____________

Country of birth: __________________ Handedness: __________________

If not born in Canada, when did your child come to Canada? (Month/Year) ______________

The following information refers to PARENTS:

Country of birth of MOTHER: __________________

If not born in Canada, when did the mother come to Canada? (Month/Year) ______________

What language(s) does the mother speak? (please list) __________________________

________________________________________________________

Country of birth of FATHER: __________________

If not born in Canada, when did the father come to Canada? (Month/Year) ______________

What language(s) does the father speak? (please list) __________________________

________________________________________________________
Please indicate the highest level of education and occupation for each parent:

<table>
<thead>
<tr>
<th>Mother</th>
<th>Father</th>
</tr>
</thead>
<tbody>
<tr>
<td>_____</td>
<td>_____</td>
</tr>
<tr>
<td>No high school diploma</td>
<td>No high school diploma</td>
</tr>
<tr>
<td>High school graduate</td>
<td>High school graduate</td>
</tr>
<tr>
<td>Some college or college diploma</td>
<td>Some college or college diploma</td>
</tr>
<tr>
<td>Bachelor’s Degree</td>
<td>Bachelor’s Degree</td>
</tr>
<tr>
<td>Graduate or professional degree</td>
<td>Graduate or professional degree</td>
</tr>
</tbody>
</table>

Occupation: ________________  Occupation: ________________

**PART B:** Please answer the following questions about your child’s language abilities:

1. a) What language did your child first speak?
   - English
   - Other language (Please specify: ________________ )  Both

2. a) Where did your child learn English?
   - Home
   - School
   - Community
   - Other: ______________________________

   b) Where does your child speak English now (circle all that apply)?
   - Home
   - School
   - Community
   - Other: ______________________________

3. a) Does your child understand any language other than English?  Yes  No
   - If Yes, what language(s)? _____________________________________________

   How would you rate your child’s understanding of the other language?  Excellent  Fair  Poor

   How would you rate your child's understanding of English?  Excellent  Fair  Poor

   b) Does your child speak any language other than English?  Yes  No
   - If Yes, what language(s)? _____________________________________________
How would you rate your child’s speaking ability of the other language?

Excellent  Fair  Poor

How would you rate your child’s speaking ability in English?

Excellent  Fair  Poor

4. a) If your child speaks any other language, other than English, where did your child learn the other language?

Home  School  Community  Other: _________________________  N/A

b) At what age did your child begin learning the other language(s)? ____________________________

c) How often does your child speak the other language(s) now?

Daily  Weekly  Monthly  Occasionally  Other: ______________  N/A

d) Where does your child speak this other language(s) (circle all that apply)?

Home  School  Family  Other: _________________________  N/A

5. a) Does your child attend any language or school program other than regular school?  Yes  No

If Yes, what program? __________________________________________________________

How often does your child attend this program?

Everyday  Once a week  Other: __________________________

When did your child begin this program? ____________________________________________
**PART C:**

We would like to know more about the languages used in your home. Please think about a typical week in your child’s life. Please fill out the percentage of time that he/she uses English and any other language(s) when engaged in the following activities:  
Note: this information may pertain to child OR parents. **Please read carefully.**

<table>
<thead>
<tr>
<th>Activity</th>
<th>English</th>
<th>Second Language (please specify):</th>
<th>Third Language (please specify):</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Language spoken by your child to parents</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language spoken by child to siblings</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language spoken by child to other family members</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language spoken by child to friends</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language spoken among adults at home</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language spoken by parents to your child</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language spoken by other family members to your child</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language in which your child watches TV/videos</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language in which parents watch TV/videos</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language in which parents and child read stories together</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language in which parents read Newspaper/Books</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
<tr>
<td>Language child uses during extra-curricular activities (e.g., sports, music lessons etc.)</td>
<td></td>
<td></td>
<td></td>
<td>=100%</td>
</tr>
<tr>
<td>Overall estimate of your child’s language environment</td>
<td></td>
<td></td>
<td></td>
<td>= 100%</td>
</tr>
</tbody>
</table>
PART D:

We would like to know more about your child’s musical experience. Please answer the following questions.

1. Has your child ever taken music lessons? Yes  No

   If YES please answer the following:

   Private Lessons ______  Group Lessons ______  School/day care Instruction ______  
   Voice ______  Instrument (Please specify: ______________________)
   Date lessons began: ______________________
   Number of lessons per week: ______________________
   Length of each lesson: ______________________
   Does your child practice at home between lessons? Yes  No
   How many minutes does he/she practice each day? ________ minutes
   Total amount of musical training (months) ______________________
   * Please count one full year of lessons as 10 months (September to June)

2. Does your child listen to music at home? Yes  No

   If YES, what kind of music does your child prefer to listen to?

   ______________________________________________________________
   ______________________________________________________________

3. Is either parent a musician (i.e., professional or hobby) Yes  No

   If YES, please describe (i.e which instrument, how many times per week are you playing?).

   ______________________________________________________________
   ______________________________________________________________
PART E:

We would like to know more about your child’s visual art experience. Please answer the following questions.

1. Has your child ever taken art lessons?  Yes  No

   If YES please answer the following:
   
   Private Lessons ______  Group Lessons ______  School/day care Instruction ______
   
   Medium (e.g. drawing, painting, pottery, etc.) ________________________________
   
   Date lessons began: _________________________________________________________
   
   Number of lessons per week: _______________________________________________
   
   Length of each lesson: _____________________________________________________
   
   Does your child practice at home between lessons?  Yes  No

   How many minutes does he/she practice each day? ________ minutes
   
Total amount of visual art training (months) ____________________________

* Please count one full year of lessons as 10 months (September to June)

2. Is either parent an artist? (i.e., professional or hobby)  Yes  No

   If YES, please describe.

   _______________________________________________________________________
   
   _______________________________________________________________________

   _______________________________________________________________________

   _______________________________________________________________________

   _______________________________________________________________________

   _______________________________________________________________________

   _______________________________________________________________________

   _______________________________________________________________________