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Error-related negativity (ERN) and 'hot' executive function in bilingual and monolingual preschoolers

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Abstract

Early regular experience with dual-language management is thought to shape executive function (EF) circuitry during development. However, previous investigations of bilingual children's EF have largely focused on behavioral measures, or on cognitive aspects of EF. The first part of this study compared monolingual and bilingual preschoolers' performance on more purely cognitive and more affective versions of a card-sort task, and the second part investigated Error-related negativity (ERN) event-related potential (ERP) waveforms to understand error-awareness mechanisms underlying task performance. Behavioral results showed bilingual advantages in reaction times but not accuracy, and interaction effects of language background, level of challenge, and affective/motivational salience on reaction times. Electrophysiological results revealed smaller ERN peak amplitudes in bilinguals compared to monolinguals in frontal and frontocentral midline regions. Results highlight that bilingualism may shape motivational mechanisms and neural learning mechanisms such as error-detection, such that bilinguals may be less focused on their errors.

Introduction

Studies of bilinguals' neurocognitive abilities have recently brought the executive function (EF) system into the spotlight. EF comprises higher order skills such as working memory, cognitive flexibility, and inhibitory control. A host of studies has tested the 'bilingual advantage' hypothesis: the idea that early experiences with bilingualism may confer certain advantages onto bilinguals' EF skills, compared to monolinguals. In young children, bilingual advantages in EF skills have been shown across various tasks (Bialystok, Barac, Blaye & Poulin-Dubois, 2010; Bialystok & Feng, 2009; Bialystok & Martin, 2004; Carlson & Meltzoff, 2008; Martin-Rhee & Bialystok, 2008) and in different cultures (see Barac & Bialystok, 2012 for review; Bialystok & Viswanathan, 2009). On the other hand, some studies in adults have reported a lack of bilingual advantages (Duñabeitia & Carreiras, 2015; Paap, 2014; Paap & Greenberg, 2013; Paap, Johnson & Sawi, 2015), suggesting that early advantages may become muted at stages of peak cognitive ability.

Bilingual advantages continue to garner much attention, with an emphasis on efforts to understand underlying mechanisms by which bilingualism may shape the EF system (see Valian, 2015 for discussion). Currently, bilingual advantages, where they appear, are attributed to processes of experience-dependent plasticity in the frontal and prefrontal brain networks associated with EF. That is, early and regular experience with dual-language management are thought to shape EF circuitry, leading to cognitive benefits (Grundy, Anderson & Bialystok, 2017). While bilingualism is thought to shape the structure and function of the EF system, we know very little about its rapidly developing neural mechanisms in bilingual children.

Further, while many studies have carried out behavioral investigations in school-aged children, we have relatively little understanding of bilingual advantages in preschoolers. For example, in their meta-analysis of studies investigating cognitive correlates of bilingualism, Adesope, Lavin, Thompson and Ungerleider (2010) reported 7 publications involving Pre-K aged children of a total of 63 studies systematically reviewed. This includes a study with a Pre-K to Grade 1 age range. However, the preschool period is a time of emerging EF skills and rapid development (Anderson, 2002; Dowsett & Livesey, 2000; Garon, Bryson & Smith, 2008; Weintraub et al., 2014; Zelazo, Craik & Booth, 2004), making it an important developmental time period to study in this context. The development of EF in the preschool years is sensitive to a number of environmental inputs such as socio-economic stressors, and training (Brown, Ackerman & Moore, 2013; Fay-Stammbach, Hawes & Meredith, 2014; Ruberry et al., 2017; Thorell, Lindqvist & Nutley, 2009). Further, EF skills are predictive of important aspects of cognitive development in children such as school-readiness (Blair & Razza, 2007;

McClelland et al., 2007; Nesbitt, Baker-Ward & Willoughby, 2013; Shaul & Schwartz, 2014), the foundations of which are forming at preschool age. Thus, to understand how bilingualism shapes neurocognitive function, it is important to understand the early effects of this interaction.

Two distinct but interrelated EF skills are conflict inhibition (sometimes referred to as inhibitory control or interference control), and cognitive flexibility (Miyake et al., 2000). Conflict inhibition involves the control of one's attention, behavior, thoughts, and/or emotions to "override a strong internal predisposition or external lure, and instead do what's more appropriate or needed" (Diamond, 2013, p. 137). Cognitive flexibility is the ability to shift efficiently between mental sets. In preschoolers, studies have found bilingual advantages in conflict inhibition and inhibitory control using a variety of tasks including the Dimensional Change Card Sort (DCCS), Stroop tasks, the Opposite Worlds task, the Go/No-Go task, and the Attention Network Task (Barac, Moreno & Bialystok, 2016; Bialystok, 1999; Bialystok et al., 2010; Bialystok & Martin, 2004; Carlson & Meltzoff, 2008; Esposito & Baker-Ward, 2013).

While there is evidence for bilingual advantages from several studies, a lack of task standardization in the literature continues to obscure the scope and mechanisms of such an advantage. The literature broadly suggests that variations in language backgrounds, task stimuli, context, or difficulty can moderate bilingual advantages in children. To better understand the scope and mechanisms of any bilingual advantages in preschoolers' conflict inhibition and cognitive flexibility, we need tasks that can be easily compared across studies, and modified for different contexts and different difficulty levels.

Measuring Cool and Hot executive function

One domain of EF that has been neglected in the bilingual advantage hypothesis literature is the consideration of 'hot' or affective EF skills. 'Cool' EF refers to the more purely cognitive aspects of EF that are more traditionally measured by EF tasks. 'Hot' EF refers to more affective aspects of EF: those measured in high-stakes or emotionally significant situations. Cool and hot EF have been associated with lateral prefrontal cortex areas, and orbitofrontal and medial cortex regions, respectively (Happaney, Zelazo & Stuss, 2004; Zelazo & Müller, 2002). Hot EF is measured by tasks such as the Children's Gambling Task, or delay of gratification tasks, and is utilized when individuals "really *care* about the problems they are attempting to solve" (Zelazo & Cunningham, 2007, p.142). There is a growing body of developmental literature exploring distinct cognitive (cool) versus affective (hot) EF systems in monolingual preschoolers and kindergarteners (e.g., Brock, Rimm-Kaufman, Nathanson & Grimm, 2009; Hongwanishkul, Happaney, Lee & Zelazo, 2005; Kerr & Zelazo, 2004; Qu & Zelazo, 2007; Zelazo & Carlson, 2012). However, it is currently difficult to compare across young children's EF performance on cool and hot tasks, due to notable differences in task design and cognitive demands. For example, currently available hot tasks require decision-making over larger time windows, with one or more real-time motivational factors at play. In contrast, cool EF tasks such as the Go-No/Go task, Flanker task, or DCCS task, require rapid responses/decisions in quick succession, often with no direct feedback or incentives. Some of these differences are captured in Carlson and Meltzoff's (2008) distinction between cool "conflict" tasks and hot "delay" tasks. Being able to more directly compare cool and hot EF systems could shed light on how neurocognitive aspects of EF are affected by motivational and emotional processes.

While hot EF has been studied in monolingual preschoolers, it has rarely been studied in bilingual preschoolers or in the context of bilingual advantages. Carlson and Meltzoff (2008) compared monolingual and bilingual preschoolers on cool conflict tasks (e.g., DCCS) and hot delay tasks (e.g., delay of gratification); however, as suggested above, the differing task demands make it hard to make neurocognitive comparisons across cool and hot contexts. Comparing these contexts would clarify if, or how, bilingualism, affect, and motivation interact to constrain or aid EF skills.

In monolingual preschoolers, cool tasks have been modified to introduce an affective component. Qu and Zelazo (2007) tested 3 year old preschoolers on the standard DCCS task (Zelazo, 2006), as well as an affective 'Emotional Faces' version, involving male and female faces that were either happy or sad. The Emotional Faces task modelled the standard DCCS, but was designed to tap into the hot EF system. Here, children sorted cards along gender or emotion dimensions (such as happy or sad), instead of the usual shape or color. In this way they were able to compare across the cool cognitive stimuli and hot affective stimuli. Results showed higher performance on the Emotional Faces task, suggesting that emotionally laden stimuli can have performance effects on EF tasks, at least in young children.

Similar to Qu and Zelazo, we have recently developed an affective, hot DCCS task, designed to tap into hot EF (Tarullo, Nayak, St John & Doan, 2018). In addition to being emotionally-significant, our hot DCCS is high-stakes and motivating, and includes trial-by-trial feedback in the form of happy or sad faces and sounds. Feedback is accompanied by 'gaining' or 'losing' sticker prizes on-screen, introducing a reward component. The hot DCCS is modified from Espinet, Anderson and Zelazo's (2012) computerized cool DCCS task, and keeps both the stimuli and rules identical to the standard cool DCCS. Through the age-appropriate feedback and rewards provided, preschoolers tend to really care about their performance on the task, helping us tap into hot EF.

Previous studies in bilingual and monolingual preschoolers have focused on DCCS 'post-switch' accuracy as a measure of cognitive flexibility (e.g., Carlson & Meltzoff, 2008). The post-switch condition refers to trials on which the initial dimensional card-sort rule (e.g., sort by shape) is switched to a new rule (e.g., sort by color). Post-switch accuracy is therefore a measure of how well preschoolers can flexibly adapt to the new rule. Based on post-switch accuracies, previous studies have reported bilingual advantages in preschoolers' cognitive flexibility (Bialystok, 1999; Bialystok & Martin, 2004; Carlson & Meltzoff, 2008). In these studies, as well as in the monolingual development literature, performance on the PRE-SWITCH condition is often considered only to indicate whether participants 'passed' or 'failed' to adhere to the initial card sort rule. However, since the pre-switch condition involves sorting cards by one of two salient dimensions, it can provide a baseline measure of conflict inhibition. Measured against this baseline, the post-switch condition provides a measure of conflict inhibition based on a new rule, and the additional EF skills required to flexibly switch to a new rule. Comparing monolinguals and bilinguals on the DCCS pre-switch skills can therefore provide additional insight into EF processing. Further, due to the availability of computerized DCCS tasks (Bialystok & Martin, 2004; Espinet et al., 2012; Qu & Zelazo, 2007; Tarullo et al.,

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2018), it is possible to measure response times (RTs) on correct card-sort trials in both pre-switch and post-switch conditions. RTs can shed light on processing speed in bilinguals relative to monolinguals. To our knowledge, previous studies of bilingual and monolingual preschoolers' DCCS performance have not considered differences in pre-switch performance or RTs.

Exploring neural mechanisms of EF in bilingual children

It is generally assumed that regular dual-language management involves control processes such as selectively inhibiting or switching between languages. Neuroimaging studies in adults show that a wide range of brain regions are implicated in bilingual language control, including those associated with executive control skills (Abutalebi & Green, 2008; Luk, De Sa & Bialystok, 2011). Currently, bilingual advantages in EF skills, where found, are attributed to cumulative experience with dual-language management and language control. However, very little is known about WHICH or HOW neural mechanisms are shaped during periods of rapid development such as early childhood. Only one published study has directly examined and compared online neural mechanisms in bilingual and monolingual children (Barac et al., 2016). In this study, 5 year old preschoolers completed a Go/No-Go task (measuring inhibitory control) while EEG electroencephalography data were recorded. Bilinguals showed better behavioral performance, and more mature electrophysiological markers of inhibition (N2) and monitoring (P3) processes, relative to monolinguals. This finding lends support to the hypothesis that bilingualism shapes neural mechanisms in early childhood, and indicates specific processes such as inhibition and conflict monitoring as potential loci of these effects. Additional EEG studies in young bilingual children are critical to further understand how bilingualism shapes the developing brain's specific mechanisms underlying behavioral skills.

While Barac et al. (2016) studied online markers of SUCCESSFUL executive processing such as N2 and P3, another way to approach our understanding of EF mechanisms in bilinguals is to examine FAILED executive processing. Specifically, how do bilingual and monolingual children learn from their mistakes? Human error-processing, indexed by the well-established frontocentral Error-Related Negativity (ERN) event-related potential (ERP) waveform, originates in the Anterior Cingulate Cortex (ACC) (Holroyd & Coles, 2002; Meyer, Weinberg, Klein & Hajcak, 2012; Velanova, Wheeler & Luna, 2008; Yeung, Botvinick & Cohen, 2004). The ACC is thought to integrate input from motivational, error detection, cognitive and emotional networks (Bush, Luu & Posner, 2000), and is therefore an important aspect of the EF system. The ERN error-detection signal indexes error-processing and is thought to aid in improvement of task performance (Holroyd & Coles, 2002). Given that ERN signals have been found in frontocentral midline regions in children as young as 4 (Brooker, Buss & Dennis, 2011), it is an excellent tool to examine how bilingualism may shape the rapidly developing EF system in preschoolers. No studies have previously compared error-processing in bilingual and monolingual children, which may be highly relevant for understanding differences in EF skills.

The current study

We measured bilingual and monolingual preschoolers' accuracy and RTs on a cool and hot version of the DCCS. We also recorded high-density EEG while participants completed both DCCS versions. The current study extends previous comparisons of bilingual and monolingual preschoolers' conflict inhibition and cognitive flexibility in the following ways: first, we focus on the preschool age, a time of rapidly developing EF skills that has been sparsely studied in the context of bilingual EF development. Second, we aim to refine our understanding of the scope and potential mechanisms of the bilingual advantage shown in preschoolers by considering the additional variables of processing speed and conflict inhibition. Further, we aim to understand how bilingualism may shape the hot EF system by comparing bilingual and monolingual preschoolers on both a cognitive cool DCCS, as well as a high-stakes hot DCCS including emotionally significant feedback and reward. Lastly, we compare neural mechanisms of error-processing in bilingual and monolingual preschoolers, by examining ERN signals during the DCCS task.

Methods

Participants

All participants were recruited from the greater Boston area in Massachusetts, USA. A total $N = 115$ participants (62 MLs; 53 BLs) between 3.5 and 4.5 years old completed the behavioral procedures. Table 1 provides demographic breakdowns of our sample, detailing Age, SES, Gender, and Ethnicity. An additional 14 participants enrolled in the study but were excluded from final analyses due to declining to participate in relevant study procedures ($n = 7$), technical difficulties ($n = 1$), not completing all relevant study procedures ($n = 1$), age information being unavailable ($n = 1$), or for being categorized as neither monolingual nor bilingual ($n = 4$).

All bilingual participants in our sample were dominant in English, and their L2s spanned a range of non-English languages. However, informed consent procedures for parents were only available in English, Chinese, and Spanish, due to the languages in which our experimenters were fluent, leading to an oversampling of children from Spanish and Chinese speaking families. Participants were categorized as monolingual if parents reported < 5% regular exposure to an L2, and as bilingual if parents reported ≥ 20% exposure to an L2. These thresholds were decided based on previous studies that suggest that children need about 10–25% exposure to each language in order to be bilingual (Marchman, Fernald & Hurtado, 2009; Place & Hoff, 2011). Within this range, some consider 20% to be the specific threshold of bilingualism (Gutiérrez–Clellen & Kreiter, 2003), which is also consistent with the finding that children are much less likely to make utterances in a second language if they are exposed to it less than 20% of the time (Pearson, Fernandez, Lewedeg & Oller, 1997).

From the total sample of preschoolers who participated in the study, a complete set of EEG data was available for 94 preschoolers. Of these 94, 21 children were excluded because they did not commit a sufficient number of errors to extract error-related ERP segments. From the 73 children remaining, a total of 48 met the inclusion criteria for usable EEG quality (i.e., at least 10 clean ERP segments). From these 48, 8 were excluded based on their classification as neither bilingual nor monolingual. Thus, the total sample available for ERP analyses of interest was $n = 40$ (19 BLs; 21 MLs). Criteria and methodology for EEG preprocessing and ERP extraction are further detailed in the Methods section below.

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Table 1. Demographic information of total sample by language group

	Monolinguals	Bilinguals
	Mean (SD)	
Age (in months)	50.2 (3.01)	49.74 (4.02)
SES (Z scores) [a]	0.14 (0.68)	−0.26 (0.99)
Income-to-needs ratio		
Parent Education	0.16 (0.68)	−0.25 (1.12)
Parent Occupational Prestige	0.25 (0.58)	−0.23 (0.96)
Annual Income	0.20 (0.87)	−0.21 (1.11)
	%	
Gender (% female)	16.38	24.14
Race/Ethnicity		
Caucasian	40.00	10.43
African-American	0.00	3.48
Hispanic/Latino	0.00	8.70
Asian	3.48	12.17
Middle-Eastern	0.00	0.87
Biracial/Multiracial	11.30	9.57

Note. $N = 115$. [a]SES is a standardized composite measure consisting of income-to-needs ratio, parent education, and parent occupational prestige. All SES components are standardized (M = 0, SD = 1).

Behavioral and demographic measures

Cool Dimensional Change Card Sort Task (Espinet et al., 2012)

The Dimensional Change Card Sort (DCCS) is a computerized task, presented using E-Prime Professional 2.0, in which children sort images based on a given dimension, e.g., sort by shape, and then sort according to a new rule after a certain number of trials. In order to sort the images successfully, children are required to inhibit attention to the competing dimension (e.g., ignore the color, and attend to the shape). The first 15 trials comprise the pre-switch condition. After 15 trials, they are required to inhibit the first rule and sort by a different rule for an additional 30 trials (e.g., sort by color). These 30 trials comprise the post-switch condition. Post-switch performance measures children's ability to flexibly adjust to a new sorting rule, along with inhibitory control. The design for the computerized Cool and Hot DCCS tasks utilized here are modelled after, and modified from, Espinet et al. (2012), as detailed in Tarullo et al. (2018). No performance feedback is offered during this task except in practice trials, and the task is thought to elicit more cool or PURELY *COGNITIVE* EF processing (Zelazo & Müller, 2002). The cool DCCS yields separate RT and accuracy scores for each trial, for both pre-switch and post-switch conditions.

Hot Dimensional Change Card Sort Task (Tarullo et al., 2018)

The hot DCCS was a modified version of the DCCS (Espinet et al., 2012), created by Tarullo et al. (2018), and included performance feedback after each trial. Importantly, the feedback is emotionally salient, such that when the child responds correctly, they see a happy face, followed by a collection of fish stickers appearing in a booklet, each accompanied by a positive sound. When the child responds incorrectly, they see a sad face, followed by a collection of fish stickers disappearing from a booklet, each accompanied by a negative sound (Fig. 1).

Before the task, the child is given an actual sticker booklet and shown the fish stickers, and it is explained that they will gain or lose stickers based on their performance. This task is thought to engage more SOCIO-EMOTIONAL PROCESSING, as described in Zelazo & Müller (2002). Similar to the cool DCCS, the hot DCCS yields separate RT and accuracy scores for each trial, for both pre-switch and post-switch conditions.

NIH Toolbox Picture Vocabulary Test

The NIH Toolbox Picture Vocabulary Test (TPVT) is a computer-adaptive measure of receptive vocabulary, and a component of the NIH Toolbox Cognition Battery. Audio recordings of words are presented along with four images, from which the child is asked to choose the image that most closely relates to the word. The measure is computer-adaptive, i.e., the words presented automatically increase in difficulty based on the child's performance. The TPVT shows excellent convergent and divergent validity as a measure of receptive vocabulary (Weintraub et al., 2013), and is modeled after other well-established vocabulary measures such as the Peabody Picture Vocabulary Test – Fourth Edition (PPVT-IV; Dunn & Dunn, 2007). The current analyses utilize an unadjusted scale score, which are theta scores ($M = 0$; $SD = 1$) calculated according to Item Response Theory (IRT).

Socioeconomic Status (SES)

Parents reported on their household's annual income and composition, highest maternal and paternal level of education attained, and maternal and paternal occupation (as applicable). From these reports, a maternal and paternal occupational prestige variable was coded using the job zone coding scheme from the Occupational Information Network (O*NET, http://www.onetonline.org/help/online/zones), which ranks U.S. census-based occupational categories on a 1–5 scale based on the education, experience, and training required. Parental educational attainment and occupational prestige were computed by averaging across maternal and paternal variables. Further, an income-to-needs ratio variable was computed from household income and composition information, using 2013 U.S. federal poverty guidelines. Parent educational attainment, parent occupational prestige, and income-to-needs ratio were standardized and averaged to create an SES composite variable.

Neural Measures

High Density EEG Recording

Dense array EEG was recorded utilizing the Clinical Geodesic EEG System 300 (Electrical Geodesics, Inc.), consisting of a 128-channel Hydrocel GSN 130 net, Net Amps 300 Amplifier, an experimental station with E-Prime Professional 2.0 (Psychology Software Tools) and E-Prime Extensions for Net Station, and Net Station 4.5 software. While consent and assent were collected, the EEG net was soaked for 10 minutes in a hot Potassium Chloride solution. EEG recordings were collected while the child was seated inside the electrically shielded EEG booth. Before recording began, impedances were checked and electrodes were adjusted till impedances were below a threshold of 80 Ω, an adequate level of impedance for research with young children

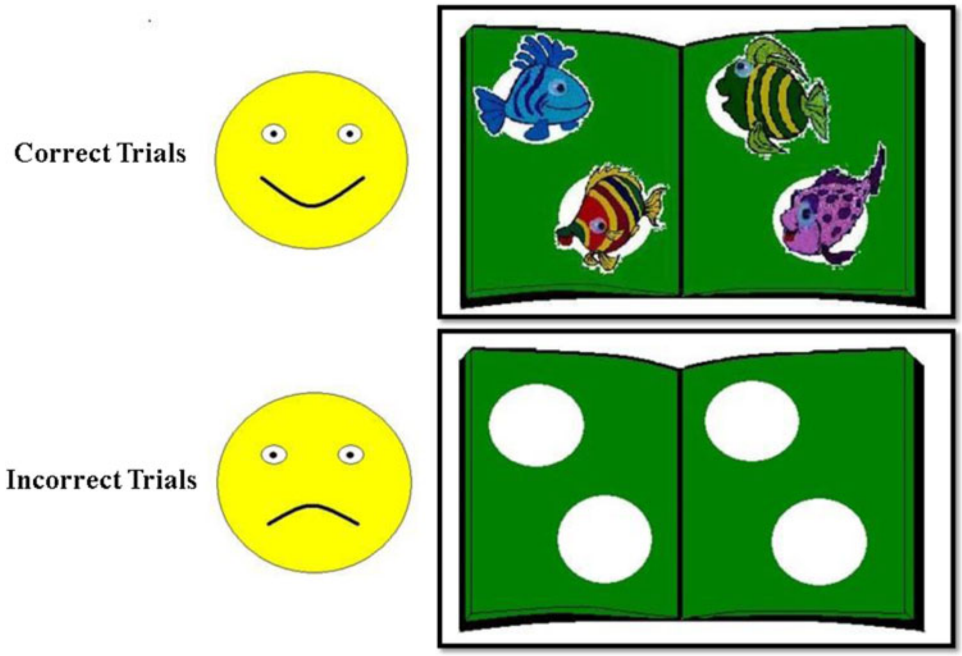

Fig. 1. The Hot Dimensional Change Card Sort task created by Tarullo et al. (2018), modified from Espinet et al. (2012). After correct trials, children see a happy face, followed by an animation of a booklet filling up with stickers (end point of animation illustrated here). After incorrect trials, children see a sad face, followed by an animation of stickers disappearing from a booklet (end point of animation illustrated here).

using a high-impedance EEG acquisition system. EEG was recorded to a vertex reference at a 500 Hz sampling rate.

Offline EEG Processing and Extraction of Error-Related Negativity (ERN)

Offline, a bandpass filter of 1–30 Hz was applied and data was segmented into epochs, time-locked to the onset of participants' responses. Based on previous literature pertaining to this age group, the time window for the response-locked segment extracted was from – 300 to 300 ms relative to response. Segment length was chosen to include both the baseline window and the window of interest for extracting ERNs. EEG data from the conditions of interest were segmented (cool DCCS pre-switch incorrect trials.

For each segment, an automatic artifact rejection paradigm identified channels with excessive artifact (>200 µV), and replaced bad channels via interpolation. Next, the Ocular Artifact Removal tool in NetStation 4.0 was used to excise eyeblink artifacts from the data with a 20 µV/ms blink slope threshold, and the cleaned data were again subjected to artifact rejection and bad channel replacement. Channels that were bad on >15% of the segments were marked as bad for the entire recording. Segments with >15 bad channels or with remaining eyeblinks (>140 µV differential average) were excluded. Individual ERPs were then re-referenced to an average reference, and baseline corrected against a window of 200 ms, between -300 and -100 ms prior to response latency. ERP segments were grand-averaged and visualized for monolinguals and bilinguals, with participants with a minimum of 10 clean segments included in the grand averages. Visual inspection of grand averages showed ERN-like activity clustered in the frontocentral midline region, with some activity in frontal and central areas, as expected, although waveform morphology looked different closer to central areas, in the grand averaged visualization. Only participants with a minimum of 10 clean ERP segments were included in the grand average, consistent with previous ERN analyses in children and adults which have found that as few as 6 clean segments can be used for ERNs (Grammer, Carrasco, Gehring & Morrison, 2014). In our sample, a total of 40 participants (21 MLs; 19BLs) had the minimum required clean segments. Based on initial inspection, and where the ERN is inspected in young children, three regions of interest (ROIs) were created in order to extract pooled ERN amplitude and latency data from frontal, frontocentral, and central channels. Next, individual-waveform averages, averaging across good ERP segments, were examined in the ROIs to ensure that the ERN fell within the defined window. When needed, the window was adjusted slightly to contain the ERN waveform. Pooled ERN amplitudes and latencies-to-peak were then extracted from ROIs, where the ERN was defined as the most negative peak within -100 ms and 100 ms of incorrect responses. These parameters for ERN extraction are consistent with other investigations of the ERN in children (Brooker et al., 2011; Meyer et al., 2012). Overall, participants included in ERN grand averages had a mean of 16.7 usable incorrect trials ranging from 6 to 28 trials. Of this, monolinguals had on average 17.9 usable trials, and bilinguals had 15.4 usable trials. Monolingual and bilingual grand averages included 308 and 285 incorrect trials respectively, totaling 593. ERN amplitudes and latencies-to-peak were computed by averaging across clean segments from the pre-switch and post-switch conditions of the cool DCCS task. The mean number of usable trials per participant in the pre-switch condition was 4.24 (ranging from 1 to 10), and in the post-switch condition was 12.04 (ranging from 4 to 26). Due to the overall high number of correct responses in the hot DCCS task (Tarullo et al., 2018), and a high proportion of unusable incorrect response segments, it was not possible to compare monolingual and bilingual ERNs in the hot DCCS.

Procedures

Children between the ages of 3.5 and 4.5 years visited the laboratory with their parent to participate in the study, which lasted 2 hours. After informed consent was obtained, children completed the cool and hot DCCS tasks as measures of inhibitory control while high density EEG was recorded. Next, they completed the TPVT as a measure of receptive vocabulary. Since the TPVT can be fairly time-consuming, tasks involving EEG recording were completed first to avoid fatigue and restlessness in the children for cleaner EEG acquisition. All study procedures were approved by the Institutional Review Board.

EEG data collected was processed offline, and Error-Related Negativity (ERN) amplitudes and latencies were extracted. During the EEG recording phase, all participants completed the cool task first, and then the hot, affective task. That is, the order of cool and hot DCCS tasks was not counterbalanced. This order was consistently maintained for each participant so that the more purely cognitive task (no feedback or rewards) would not be influenced in any way by the motivation or affect elicited by the hot DCCS task (both feedback and rewards). This technique has been used previously with these tasks (Tarullo et al., 2018).

Once the cool, more purely cognitive phase of testing was complete, small prizes and stickers were given to children throughout the rest of the procedures, to keep them motivated. While the children completed the tasks, parents completed demographic questionnaires and completed cognitive tests. In addition to the study procedures mentioned here, children's inhibitory control and attention skills were also measured, as reported in Tarullo et al. (2018). These tasks were completed after the EEG recording phase. Results of these additional procedures will not be discussed in the present study.

Analyses

Planned behavioral analyses

We first analyzed any differences between monolinguals and bilinguals on background variables of interest: Age, SES, and TPVT scores. Mean accuracies and RTs were then computed for each participant, separately for pre-switch and post-switch conditions of the cool and hot DCCS. Accuracy referred to the proportion of correct trials within a condition, and RTs were averaged across correct trials only. Trial RTs <150 ms or >10 s were removed before participant means were calculated.

Of the $N = 115$ who completed the DCCS tasks, 96 children (52 MLs; 44 BLs) adequately passed the Cool DCCS pre-switch, and 84 children (46 MLs; 38 MLs) passed the Hot DCCS pre-switch. Only children who had passed the pre-switch condition were included in the post-switch analyses. Participants were deemed to have "passed" the pre-switch condition if they responded correctly to at least 11/15 trials, consistent with Espinet et al. (2012) and Tarullo et al. (2018).

Based on our interest in understanding any effects of language background in performance measures (RTs and accuracies) and in understanding this relationship in 2 DCCS types (Cool/Hot) X 2 conditions (pre-switch/post-switch), we conducted 4 Multivariate ANCOVAs, with RTs and accuracies as the dependent variables, language background as the between-subjects factor, and Age, SES, and TPVT scores as covariates. It was important to analyze task performance separately in the 2 conditions (pre-switch/post-switch) X 2 DCCS types (Cool/Hot) such that models analyzing pre-switch performance included all participants, and models analyzing post-switch performance only included those who passed the pre-switch condition, consistent with prior work (Espinet et al., 2012; Tarullo et al., 2018).

Planned ERN analyses

EEG data were statistically extracted using NetStation and analyzed using SPSS. EEG data were then cleaned through a set of preliminary analyses, similar to those described above for behavioral analyses. In order to test for differences between language groups, we created three main regions of analyses (ROIs) where ERNs are expected in children, spanning frontal, frontocentral, and central electrode clusters. Since ROIs can be created in a number of different specific ways from a high-density net, we chose to create non-overlapping clusters of electrodes immediately adjacent to Fz, FCZ, and Cz in the 10–10 universal system. To determine equivalents, we used the mapping provided by EGI's technical note (Luu & Ferree, 2000). Based on their mapping, Fz = 11; FCz = 6, and Cz = 129 (VRef), in the Hydrocel 128 channel net. Therefore, the Frontal ROI consisted of channel 11 (Fz), and adjacent channels 19, 18, 16, 10, and 4. Similarly, the Frontocentral ROI consisted of channels 6 (FCz), and adjacent channels 13, 12, 5, and 112. Lastly, the Central ROI consisted of channels 31, 7, 106, 80, and 55. Channel 129 (Cz) was excluded from the cluster because it was the reference electrode.

To test for any differences between monolinguals and bilinguals, we conducted a repeated-measures GLM (MANCOVA) with ERN amplitudes and latencies as dependent variables, language background as the between-subjects factor, and ROIs as the within-subjects factor. Covariates were selected for the model based on whether Age, SES, or TPVT scores were significantly correlated with ERN measures. We chose to use this method of covariate selection to avoid over-fitting the planned model to poorly predictive covariates, given the smaller number of participants available in each group for ERN analyses.

In order to understand any differential associations between behavioral and neural variables in bilingual and monolingual children, we conducted correlational analyses separately in the two groups. Specifically, Bivariate Pearson Correlations were conducted between 6 behavioral variables: Cool pre-switch and post-switch accuracies, Cool pre-switch and post-switch RTs, and Cool switch costs in accuracies and RTs; and ERN variables: frontal, frontocentral, and central ERN amplitudes and latencies. Correlational analyses between behavioral and ERN data were limited to the Cool DCCS type, since ERN data were only derived from Cool pre-switch and post-switch conditions.

Results

Behavioral results

Two-tailed independent sample t-tests showed that bilinguals had smaller receptive vocabularies (TPVT scores) than monolinguals ($t = 2.61$, $df = 95$, $p < .05$). Bilingual participants were also from lower SES backgrounds compared to monolinguals ($t = 2.49$, $df = 99.4$; $p < .05$). Participants' mean age (in months) did not differ significantly between groups. MANCOVA model #1 ($n = 100$; 54 MLs, 46 BLs) tested the effects of Language Background when controlling for background variables (Age, SES, TPVT scores) on Cool pre-switch performance. Results showed a multivariate

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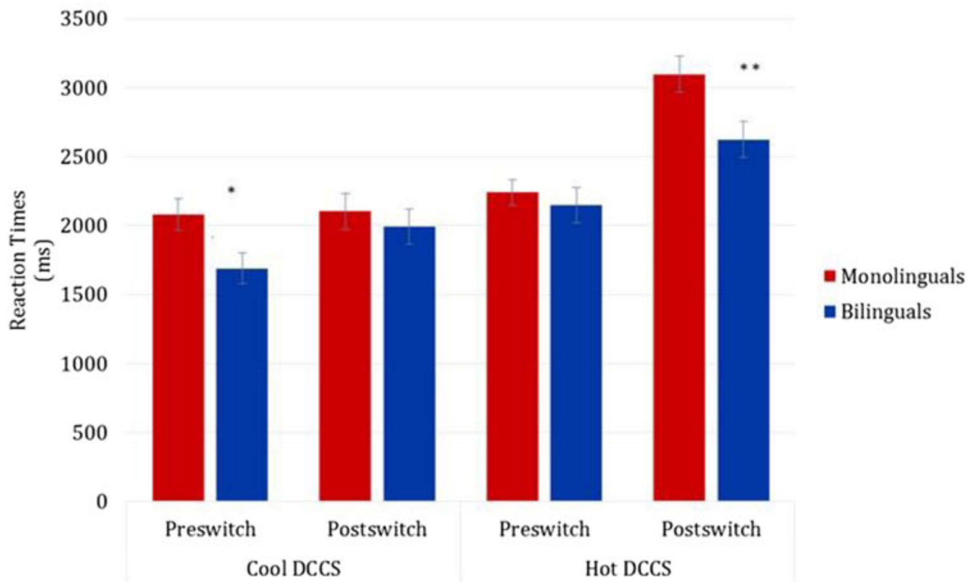

Fig. 2. Monolingual and bilingual preschoolers' RTs on pre-switch and post-switch conditions of the DCCS. Mean RTs are shown in milliseconds. RTs are given for cool and hot DCCS versions. $^*p < .05$, $^{**}p = .01$.

effect of language background on performance (F (2, 94) = 5.20, $p < .01$), driven by a main effect of language background on Cool pre-switch RTs, with bilingual children showing faster RTs than monolinguals (F (1, 95) = 10.43, $p < .01$). No group differences were found in Cool pre-switch accuracies. MANCOVA model #2 ($n = 71$; 38 MLs, 33 BLs) tested for effects on Cool post-switch performance. The model only included those participants who had successfully passed the pre-switch condition. Results showed no effect of language background on performance. MANCOVA model #3 ($n = 89$; 48 MLs, 41 BLs) tested for effects on Hot pre-switch performance. Results showed no effect of language background on performance. Lastly, MANCOVA model #4 ($n = 80$; 44 MLs, 36 BLs) tested for effects on Hot post-switch performance. Again, the model only included those participants who had successfully passed the Hot pre-switch condition. Results showed multivariate effects of Language Background on performance (F (2, 74) = 3.17, $p < .05$), driven by bilinguals showing faster RTs than monolinguals (F (1, 82) = 5.628, $p = .01$). Results showed no effect of Language Background on Hot post-switch accuracy. Figure 2 summarizes the patterns of similarity and difference in monolingual and bilingual RTs across condition and DCCS type, along with patterns of switch costs.

The above MANCOVA models also revealed certain unique effects of Age, SES, and TPVT on DCCS performance. The Cool DCCS models showed a unique effect of Age on pre-switch accuracies ($\eta^2 = .14$, $p < .01$), and of TPVT scores on higher post-switch accuracies ($\eta^2 = .06$, $p < .05$), after accounting for other factors of interest. In the context of the more affective Hot DCCS models, there was a unique effect of Age ($\eta^2 = .14$, $p < .001$) on pre-switch accuracies, and of Age ($\eta^2 = .17$, $p < .001$), SES ($\eta^2 = .06$, $p < .05$) and TPVT scores ($\eta^2 = .06$, $p < .05$) on post-switch accuracies. Notably, no unique effects of background variables were found on RTs. Table 2 details monolingual and bilingual RTs and accuracy in pre-switch and post-switch conditions of the cool and hot DCCS versions, and switch costs in performance.

ERN results

As discussed above, the mean number of error trials did not differ between monolingual and bilingual children. Preliminary correlational analyses showed that children from lower SES families showed longer ERN latencies-to-peak in the central ROI ($r = -.36$, $p < .05$). Age and TPVT scores were not associated with ERNs in the overall sample. Bivariate correlational analyses between performance and ERN measures showed that, in our sample, higher Cool pre-switch accuracies were associated with shorter ERN latencies-to-peak ($r = -.32$, $p < .05$). While we did not have usable data for ERNs elicited during the Hot DCCS, shorter ERN latencies-to-peak in the Central ROI were correlated with higher Hot post-switch accuracies in our sample.

Table 3 shows means and SEs of ERN amplitudes and latencies-to-peak in monolinguals and bilinguals, and Figure 3 illustrates the similarities and differences in monolingual and bilingual ERN grand-averaged waveforms in frontal, frontocentral, and central ROIs. A 3 X 2 repeated measures MANCOVA model, with ROIs as the within-subject factor and Language Background as the between-subjects factor, showed no multivariate effects of Language Background on overall ERN measures when controlling for Age, SES, and TPVT scores. However, there was a main effect of Language Background on ERN amplitudes (F (1, 34) = 5.65, $p < .05$, $\eta^2 = .14$). Post-hoc testing, with Bonferroni corrections, showed smaller ERN amplitudes in bilinguals in frontal (t (1, 39) = 7.42, $p = .01$) and frontocentral amplitudes (t (1, 37) = 7.30, $p = .01$).

No group differences were found in ERN amplitudes in the central ROI, nor in latencies in any ROI. Further there were no main effects of ROIs, and no Language Background X ROI interaction effects, on ERN measures. While SES was correlated with ERN latencies as discussed above, there was no unique effect of Age, SES, or TPVT scores in the MANCOVA model accounting for all background variables and Language Background.

Bivariate Pearson correlational analyses showed that, in bilingual preschoolers, higher cool pre-switch accuracies were significantly correlated with shorter frontocentral ERN latencies-to-peak ($r = -.456$, $p = .05$), whereas, in monolingual

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Table 2. Cool and hot DCCS performance by language group

		Cool DCCS					Hot DCCS				
		Pre-Switch		*Post-Switch* [a]			*Pre-Switch*		*Post-Switch* [a]		
		Mean	SD	Mean	SD	*Switch Cost* [c]	Mean	SD	Mean	SD	*Switch Cost* [c]
MLs	**ACC**	.89	.09	.74	.30	−0.15	.96	.11	.85	.25	−0.11
	RT [b]	1888.01	683.76	2101.95	861.31	213.94	2204.21	686.79	3098.16	919.70	893.95
BLs	**ACC**	.88	.09	.68	.33	−0.20	.96	.09	.84	.23	−0.12
	RT [b]	1549.34	541.47	1994.10	781.69	444.76	2212.81	851.48	2623.62	857.94	410.81

Note. [a] Only participants who passed the pre-switch conditions were included in the post-switch conditions. [b] Mean RT calculations included accurate trials only. [c] Larger switch cost values represent greater costs in performance when switching card-sort rules.

Table 3. Error-related negativity (ERN) amplitudes and latencies by region of interesting (ROI) and language background

		Monolingual	Bilingual
		Mean (SD)	
Frontal	**Amp**	−7.99 (1.15)	−3.93 (0.92)
	Lat	0.21 (10.37)	−8.63 (9.93)
Frontocentral	**Amp**	−6.81 (0.75)	−3.32 (1.06)
	Lat	3.33 (9.98)	−10.63 (8.92)
Central	**Amp**	−5.46 (0.59)	−4.11 (0.79)
	Lat	0.76 (11.61)	3.81 (9.41)

Note. N = 40 (21 MLs; 19 BLs). Cool DCCS pre-switch and post-switch incorrect trial segments were averaged to compute ERN peak amplitudes and latencies.

preschoolers, higher cool pre-switch accuracies were significantly correlated with shorter central ERN latencies-to-peak (r = -.495, p = .02). No other behavioral and ERN variables were significantly correlated, or differentially correlated, in the two groups.

Discussion

This study compared monolingual and bilingual preschoolers' performance on cool (more purely cognitive) and hot (more affective) versions of a DCCS task. Both versions matched each other closely, and tapped into conflict inhibition and cognitive flexibility skills. When no feedback or rewards were present, bilinguals were faster than monolinguals on the easier conflict inhibition condition, but, when feedback and reward were present, bilinguals were faster than monolinguals on the more challenging cognitive flexibility condition. In addition to behavioral task performance, response-locked ERNs were extracted from high-density EEG to understand error-processing mechanisms during the card sort task. Bilinguals showed smaller ERN amplitudes in frontal and frontocentral midline regions compared to monolinguals. ERNs in the central region of interest were equivalent across groups, and there were no differences in ERN latencies.

When no feedback or rewards were provided (cool DCCS), bilingual preschoolers performed better than monolingual peers on the INITIAL pre-rule switch card-sorting rule. Specifically, while both groups sorted a similar number of cards correctly, bilinguals did this faster than monolinguals. However, this bilingual advantage was no longer seen once the card-sort rule was SWITCHED (post-rule switch) to something new. It has previously been shown that most 3-year-olds find it challenging to flexibly change rules in a DCCS task, with a large number of children perseverating on the initial rule (reviewed in Hanania & Smith, 2010). Our results showed that bilingual and monolingual preschoolers found flexible switching equally challenging in the absence of any feedback.

When socio-emotionally salient feedback was provided on a trial-by-trial basis, and the stakes were high, the pattern of the bilingual advantage was different. Here, both groups performed similarly on the INITIAL card sort rule, suggesting that feedback and higher stakes overrode any bilingual advantage seen in the cool condition. However, bilingual preschoolers performed better than monolingual peers on the SWITCHED card-sort rule. Again, this bilingual advantage was reflected in faster, but not more accurate, performance.

When examining differences between cool and hot DCCS types, results showed that bilinguals were faster than monolinguals on the pre-switch condition in the cool DCCS, but faster on the post-switch condition in the hot DCCS. This in turn sheds light on the reversal in switch cost patterns (differences between post-switch and pre-switch conditions) seen between the cool and hot DCCS types: bilinguals experienced larger switch costs in the Cool DCCS, but smaller switch costs in the Hot DCCS. This pattern can be further explained by the finding that bilinguals performed faster in the baseline/initial pre-switch condition (Cool pre-switch), but, when the rule changes, bilinguals appear to slow down in response to the new task demands, resulting in larger switch costs than monolinguals, while maintaining equivalent accuracy.

In the Hot DCCS on the other hand – which rewards accuracy by design – bilinguals and monolinguals start out in the pre-switch condition with equivalent levels of performance, but when the children's overall investment in accuracy is combined with a harder task (a switched rule; having to suppress perseveration on the old rule), bilinguals once again show an advantage in speed. It is noteworthy that this pattern is driven by a greater slowing in monolinguals in the post-switch condition, compared to the pre-switch condition. While both groups seem to slow down between cool and hot DCCS versions (most likely to focus on accuracy), the overall pattern suggests that bilingual preschoolers prioritize speed over accuracy more so than monolinguals.

Taken together, our behavioral results indicate the moderating and interacting effects of TASK DIFFICULTY as well as

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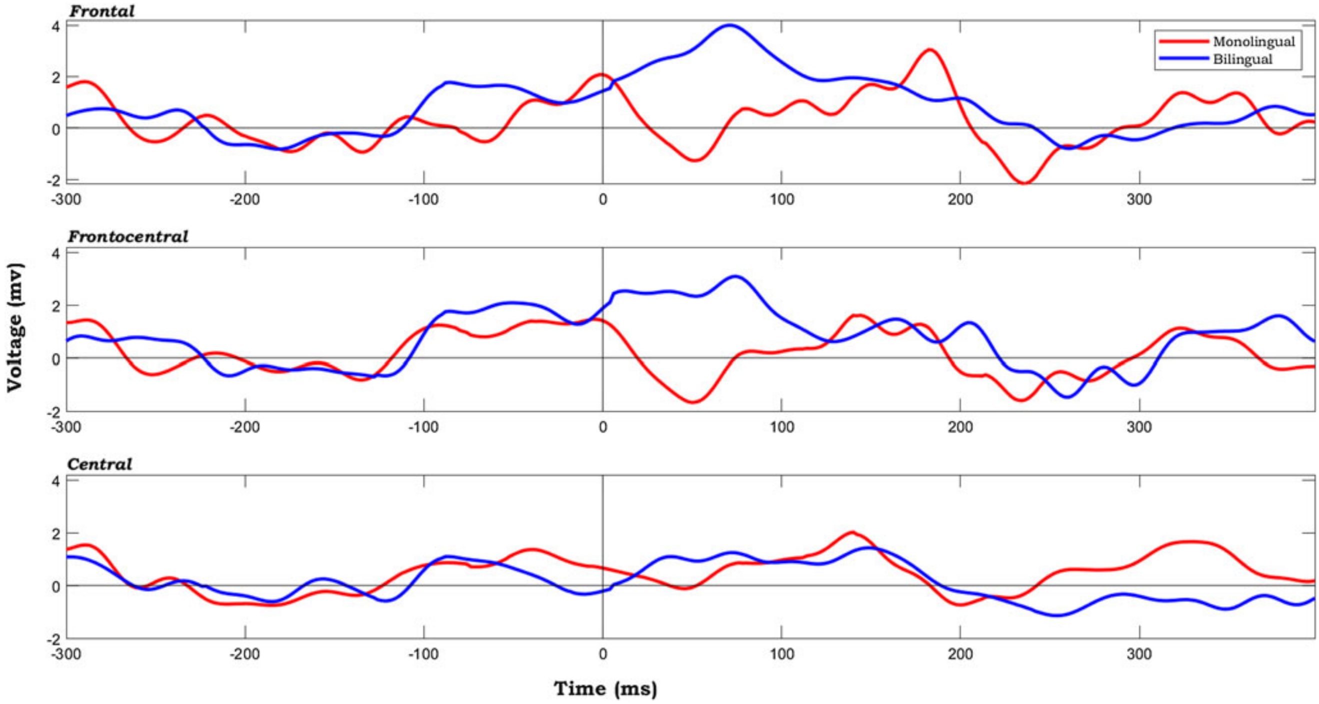

Fig. 3. Grand-averaged response-locked error-related negativities (ERNs) in bilingual and monolingual preschoolers in frontal, frontocentral, and central midline regions of interest. Baseline extends from -300 ms to -100 ms. ERN peaks are the most negative peak between -100 ms and 100 ms relative to incorrect responses.

socio-emotional STAKE and FEEDBACK, in eliciting the often cited bilingual advantage in EF. That is, bilinguals did show some advantages on conflict management and cognitive flexibility, but only when the task was either relatively EASIER in a low stakes context, or relatively MORE CHALLENGING in a high stakes context. The hot, high stakes context in our study further included the support of trial-by-trial feedback, potentially enabling preschoolers to improve their performance. This pattern suggests that bilingual advantages in inhibitory control and flexible switching appear at moderate levels of challenge; with task difficulty, socio-emotional stakes, and feedback, working as complementary forces to determine likely performance levels. This pattern of findings is particularly relevant in the age group tested here, since the preschool years are a time of significant and rapid EF development (Zelazo, Müller & Frye, 2003).

Bilinguals showed smaller (less negative) ERN peak amplitudes than monolinguals on error-trials in the cool (more purely cognitive) card-sort, in frontal and frontocentral midline regions. This difference in error monitoring and awareness between bilingual and monolingual children may point to an important mechanistic difference between how bilingual and monolingual preschoolers process error. In the current study, bilingual ERNs were weaker and above baseline in frontal and frontocentral midline regions, compared to monolinguals who showed a more robust ERN response in those regions. It remains unclear whether bilingual preschoolers generated dampened error-detection signals, or simply did not generate one in these regions. However, the presence of equivalent and stronger ERN responses in the proximal central midline region suggests the former. Further, based on the negative deflection seen within the expected scalp distribution, and the similarity of waveform morphology between monolinguals and bilinguals, we argue that bilingual preschoolers did generate error-detection signals. Others also report measurable ERNs in children wherein negative peaks occur above baseline (Davies, Segalowitz and Gavin, 2004).

What, then, do the more negative ERN amplitudes in monolinguals mean? In previous studies, bigger ERN amplitudes have been associated with higher anxiety (Ladouceur, Dahl, Birmaher, Axelson & Ryan, 2006; McDermott, Westerlund, Zeanah, Nelson & Fox, 2012; Meyer et al., 2012). However, it is unlikely that a heterogeneous group of bilingual preschoolers differed systematically from monolinguals in their level of anxiety. Other developmental studies have associated higher ERN amplitudes with increases in age (Grammer, Carrasco, Gehring & Morrison, 2014; Kim, Iwaki, Imashioya, Uno & Fujita, 2007; Meyer et al., 2012). Since our sample was younger and more restricted in age than in previous studies, it is hard to draw definite conclusions about whether smaller or larger ERN responses signal a more mature ERN response.

Two pieces of evidence from adults should be considered in interpreting the ERN differences between groups. First, ERN amplitudes in adults appear to be larger when errors are made MOTIVATIONALLY SIGNIFICANT, i.e., when participants have a higher stake in their performance (Hajcak, Moser, Yeung & Simons, 2005). Thus it is possible that monolingual preschoolers are more invested in the accuracy of their performance. Consistent with Hajcak et al.'s findings, our behavioral results showed no difference in accuracy between groups in spite of ERN differences. A second piece of evidence to consider is that ERN amplitudes appear to be smaller when the goal is to be faster, and bigger when the goal is to be accurate (Gentsch, Ullsperger & Ullsperger, 2009). Our behavioral results showed that bilingual preschoolers were faster at the same level of accuracy, in at least one condition of both the cool and hot card sorts. This could indicate faster processing speeds, an increased focus on speed than accuracy, or both. Future research could attempt to measure

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participants' self-reported goals, which could possibly underlie these group difference in ERN amplitudes.

In terms of behavioral-neural associations, results showed differential correlations between task performance and error-awareness between bilingual and monolingual children, Specifically, this difference arose in the baseline cool pre-switch condition. In both groups, higher task accuracy was associated with shorter ERN latencies-to-peak, as expected; however, in bilingual children, this behavioral-neural association was in more central brain areas, compared to being in more frontocentral areas in monolinguals. These results are partly consistent with Barac et al.'s (2016) findings in 5-year-olds, wherein bilingual children's higher Go/No-Go performance was associated with shorter N2 and P3 latencies and larger amplitudes in central sites. Unlike our results however, Barac et al. only found these correlations in the bilingual children, which could be due to the different waveforms examined, or the slightly older children in the sample. These results contribute to our nascent understanding of how early bilingualism may shape behavioral – neural associations in the developing brain in terms of both function and localization.

The present study has some limitations. Our data did not yield a sufficient number of usable error segments in each group to study ERNs elicited during the affective (hot) DCCS or across more cognitive (cool) DCCS conditions. Instead we examined the average ERN across cool DCCS conditions. Since the task used here had an unequal amount of pre-switch and post-switch conditions, the conditions were differentially represented in the averaged ERNs, with higher representation from post-switch error segments. Future studies can address these limitations through the use of longer pre-switch conditions and harder tasks for this age-group. Comparing error-processing mechanisms in cool and hot versions of a conflict/inhibition task could shed light on whether motivational significance and other affective processes are driving the group difference in ERNs. Further, more research is needed to test whether the pattern found in our study persists beyond preschool.

It is also noteworthy that our bilingual group oversampled Chinese–English and Spanish–English bilingual. However, many studies of EF in bilingual and monolingual children have utilized homogenous and heterogeneous samples (as reviewed in Barac & Bialystok, 2012; Adesope et al., 2010) and, since our main measures of interest were non-linguistic, we have no theoretical reason to believe that this oversampling impacted our results. While we did not have a detailed measure of the amount of L2 exposure within bilinguals, future research can offer further insight into error-processing in bilinguals by testing for any associations between L2 exposure and ERN amplitudes.

This is the first study to consider both cool and hot EF in bilingual and monolingual preschoolers, and to compare neural indices of task-related error-processing between groups. Our study builds upon previous work reporting bilingual advantages in children's EF skills, by exploring the sparsely studied preschool years. Further, it extends previous work in preschoolers using the DCCS by measuring performance in terms of both speed and accuracy, and adding pre-switch measures as well as a condition with feedback and rewards. Last, our study of neural mechanisms underlying FAILED attempts at inhibition adds an important dimension to the previous findings surrounding successful inhibition and monitoring (Barac et al., 2016). As seen in the present study, bilingual and monolingual preschoolers seem to utilize different error-processing mechanisms, even when they achieve the same level of task performance. This is a promising result that speaks directly to early ways in which bilingualism may shape cognition, and in particular the EF system.

In contrast to our behavioral results, Bialystok (1999) found a bilingual advantage in 4-year-olds using a physical card-sort task, and Bialystok and Martin (2004) found bilingual advantages in task accuracies on 4 different versions of a computerized DCCS task in 4 and 5-year-old children. In both previous studies, all DCCS versions were cool or more purely cognitive in nature. The inconsistency in results could potentially arise due to the younger age and increased heterogeneity of our sample, which should be systematically explored in further research.

Our results indicate that any bilingual advantages in preschoolers are sensitive to socio-emotional context and feedback. In our study however, it was difficult to separate the role of feedback, from that of socio-emotional stake, or motivation. Research on motivation in adults suggests that feedback can increase intrinsic motivation because of individuals' inherent need for competence (Ryan & Deci, 2000), and just one instance of corrective feedback can improve preschoolers' performance on a new rule during a card sort (Bohlmann & Fenson, 2005). Concurrently, preschoolers' EF performance is sensitive to the expectation of rewards, leading to increased inhibitory control and decreased flexible switching when rewards are anticipated (Qu, Finestone, Qin & Reena, 2013). Future studies should attempt to disentangle the effects of motivation and reward, as they may be particularly relevant for the early development of both cool and hot EF systems. Our results here, and previously in Tarullo et al. (2018), do suggest that the role of feedback and motivation should be considered when designing studies of EF in preschool-aged children, both bilingual and monolingual.

Ultimately, the search for a nuanced understanding of bilingual EF, particularly its unique neurocognitive features, can provide a window into developmental mechanisms relevant to executive function more broadly, such as motivation, feedback and learning, and neuroplasticity.

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