The domain-general cognitive control process in bilingual switching: evidence from midfrontal theta oscillations

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Abstract

Language control in bilingual speakers involves effectively switching between languages, inhibiting the non-intended language, and continuously monitoring speech errors. It has been a matter of controversy concerning whether language control operates in a comparable manner to cognitive control processes in non-linguistic domains (domain-general) or if it is exclusive to language processing (domain-specific). Midfrontal theta oscillations have been considered as an index for increased cognitive control, so examining whether a similar midfrontal theta effect is likewise evident in bilingual language will bring new insights to the ongoing debate. This study aimed to explore midfrontal theta oscillations in bilingual control with a specific focus on three fundamental control processes: language switching, inhibitory control, and speech monitoring. We reanalysed the EEG data obtained from two previous language switching studies where Dutch-English bilinguals named pictures based on colour cues. Theta power increase was observed during language switching, specifically in switch trials compared to repeat trials, and this effect was observed in the midfrontal region. Similarly, enhanced midfrontal theta power was observed during error monitoring, specifically when participants failed to select the intended language at a switch, compared to correct responses. However, no midfrontal theta effect was found during inhibitory control, reflected by a missing modulation in switch trials following a short run (i.e., a short sequence of same-language repeat trials) compared to a long run (i.e., a long sequence of same-language repeat trials). These findings largely support the involvement of domain-general cognitive control mechanisms in language control, particularly in language switching and speech monitoring, whereas inhibitory control remains unclear.

Layman's Abstract

Bilingual speakers seem to effortlessly switch languages, like English and Dutch. However, behind this effortlessness lies a skill called "language control" that manages their languages. Language control include processes like switching languages, preventing the unintended language, and catching speech mistakes. In daily lives, we also use control skills beyond language. Imagine changing tasks while driving, saying "no" to cakes when you are on a diet, or checking errors while typing. These are known as "cognitive control" skills. Just as bilinguals control their languages, we all need to control our actions and minds to function well. Here is a question: does language control work like general cognitive control or it is specific to language?

There are brain waves called "midfrontal theta oscillations" that occur at a certain speed (4-8 Hz) in the middle front part of our brain. They show up when we need more control over our actions. If the same brain activities occur when bilinguals control their languages, it could mean language and general cognitive control work similarly.

This study looked at how midfrontal theta oscillations work in bilingual language control. We reanalysed the data from earlier studies by Zheng et al. in 2018 and 2020. In these studies, Dutch-English bilinguals were asked to name pictures using the language indicated by colour cues. We wanted to know how bilinguals switch languages, so we compared when they switched languages to when they stayed the same one. To see how they prevent the unintended language, we played around with how long they used the same language before switching. We guessed that switching after a shorter time might need more control because using the same language repeatedly could make switching easier. Additionally, we looked at when people made mistakes switching languages and when they did it right. Here is what we found: when bilinguals switched languages and checked for mistakes, we saw midfrontal theta oscillations. This suggests that controlling languages is like controlling our actions. However, we did not see those brain waves when bilinguals prevented the unintended language. This shows that language and general control might work somewhat differently.

INTRODUCTION

Language Control in Bilingual Speech Production

In natural conversation, bilinguals appear to show remarkable flexibility in constantly speaking in one language and switching to another given the communicative situations without difficulty. In fact, this process is not as effortless as it seems, as both languages are simultaneously activated regardless of the language being spoken (Colomé, 2001; Costa et al., 1999; Hermans et al., 1998; Starreveld et al., 2014), which necessitates a process to restrict language processing to the target language and avoid the interference from the nontarget language. This process is commonly referred to as language control.

One of the most commonly used experimental paradigms to investigate language control is cued language switching (e.g., Declerck & Philipp, 2015; Meuter & Allport, 1999; Sikora et al., 2016; Zheng et al., 2018). The cued language switching paradigm normally involves the task of naming presented items (e.g., pictures, digits) that represent words, with visual cues indicating the language in which the words should be produced. Within each block bilinguals encounter switch trials, in which they are required to switch between languages, as well as repeat trials, where they need to respond in the same language as in the previous trial. The phenomenon of language-switch cost, characterized by poorer task performance with longer reaction times (RTs) and increased error rates on switch trials compared to repeat trials, has been consistently observed in previous studies (e.g., Christoffels et al., 2007; Costa & Santesteban, 2004; Jackson et al., 2001; Verhoef et al., 2009; Zheng et al., 2018).

The primary explanation for the language-switch cost pertains to the involvement of inhibition within the language control process (Declerck & Philipp, 2015; Green, 1998; Jackson et al., 2001; Liu et al., 2014; Philipp & Koch, 2009). As per Green's (1998) inhibitory control model, in any given trial the non-target language is inhibited, and this inhibition persists into the subsequent trial. When the next trial is a switch, the persistent inhibition has to be overcome and the processing of the previously inhibited language needs to be retrieved. However, such overcoming inhibition and retrieval are not required when the next trial is a repeat, resulting in switch trials being more demanding than repeat trials. Besides, recent research strives to further understand how the overcoming inhibitory control evolves over time. By manipulating the run length, which refers to the number of repeat trials before transitioning to a switch, within the language switching paradigm, Zheng et al. (2018b, 2020) found faster responses during switches following a shorter sequence of repeat trials (i.e., a short run) compared to those following a longer sequence of repeat trials (i.e., a long run). This phenomenon is known as the run length effect (see also Meuter & Allport, 1999; Kleinman & Gollan, 2018). Zheng et al.

proposed an explanation for this effect, stating that with the repeated use of the same language, the inhibition of the non-target language decreases, making it easier to be overcome at a switch.

Besides inhibition, language control also involves the monitoring of speech (Acheson et al., 2012; Declerck et al., 2017b; Hartsuiker, 2014). Despite being proficient in language switching, bilingual speakers occasionally make language selection errors, wherein they say a word in the non-target language instead of the intended equivalent (e.g., saying the Dutch word “paraplu” instead of the English equivalent “umbrella”). These language selection errors are more frequently encountered on switch trials than repeat trials in the language switching task (Zheng et al., 2018a). To effectively control their languages in use, bilinguals are thus required to continuously monitor their language production, detect potential language-selection errors, and intervene accordingly (Gollan et al., 2011).

The aforementioned language control processes, namely language switching, inhibiting the non-target language, and speech monitoring, are considered as resembling control processes observed in diverse non-linguistic domains (Abutalebi & Green, 2008; Calabria et al., 2018; Piai & Zheng, 2019). For instance, these processes can be compared to daily activities such as selecting between two options, inhibiting the urge to eat a certain food while on a diet, and monitoring errors and accuracy in typing. These activities are indicative of the underlying cognitive control processes, also known as executive functions, which involve mental abilities crucial for adjusting and regulating habitual behaviours to achieve specific goals (Miller & Cohen, 2001).

Language Control: Domain-General or Domain-Specific?

In earlier research, language control and cognitive control were commonly studied as distinct entities, with language control believed to be governed by domain-specific language control mechanisms specifically tailored for linguistic processing (Gray & Kiran, 2016). On the other hand, executive functions in non-linguistic domains were thought to operate under domain-general cognitive control mechanisms (Niendam et al., 2012). Three fundamental and extensively studied executive functions include shifting between mental sets (“task switching”), inhibition of prepotent responses (“inhibition”), and updating and monitoring of actions and performance (“performance monitoring”; Alexander & Brown, 2010; Miyake et al., 2000). These functions are typically assessed through various paradigms, such as cued task switching (e.g., Kiesel et al., 2010; Meiran, 2000), the Go/NoGo task (e.g., Jonkman, 2006), the Stroop task (e.g., Zysset et al., 2001), the Simon task (e.g., Notebaert & Verguts, 2011), and the flanker task (e.g., Tillman & Wiens, 2011). As mentioned earlier, these control processes are also evident in bilingual speech production. In recent years, there has been an ongoing debate regarding the nature of language control (Nair et al., 2021) – whether it operates in a comparable manner to cognitive control processes in non-linguistic domains (domain-general) or if it is exclusive to language processing (domain-specific). Understanding how language control relates to cognitive control can foster collaboration between two research traditions and enable them to mutually benefit from each other's theories and methodologies, thus informing a unified theoretical framework for human brain and cognition.

Various researchers believe that language control is primarily a domain-general process. Behavioural evidence supporting this idea comes from studies that directly compared the performance between language switching and non-linguistic task switching within the same cohort of bilinguals (Declerck et al., 2017a; Prior & Gollan, 2013; Timmermeister et al., 2020). The cued task switching paradigm, commonly used to assess cognitive control (e.g., Kiesel et al., 2010), closely parallels the language switching paradigm, with the only difference being the switching of targets between two different tasks instead of two languages. Across these studies, the switch cost effect (i.e., poorer performance in switch trials compared to repeat trials) was consistently found to be closely matched between language switching and task switching in bilinguals, with identical cues and stimuli used in both contexts. Additionally, behavioural evidence highlights the bilingual advantages in executive functioning, as bilinguals consistently outperform monolinguals in various tasks spanning all cognitive domains (e.g., Bialystok, 2011; Costa et al., 2008; Prior & MacWhinney, 2010), despite arguments by Paap et al. (2015) that this phenomenon may not exist. Research has also revealed that training in language switching leads to improved cognitive control performance, particularly in tasks related to monitoring and inhibitory control (Liu et al., 2019; Prior & Gollan, 2013).

Neuroimaging evidence supporting the domain-general perspective reveals striking similarities in the neural correlates for both language control and cognitive control (Alario et al., 2006; Coderre et al., 2016; de Bruin et al., 2014; Zheng et al., 2018a, 2020). For instance, functional magnetic resonance imaging (fMRI) studies examining language switching have consistently observed increased activity in brain regions such as the lateral prefrontal cortex (Abutalebi & Green, 2008; de Bruin et al., 2014; Hernandez et al., 2000; Wang et al., 2009), the anterior cingulate cortex (ACC; Abutalebi et al., 2008, 2012; Christoffels et al., 2007; Gauvin et al., 2016; Guo et al., 2011; Rossi et al., 2021), presupplementary motor area (pre-SMA; Christoffels et al., 2007; de Bruin et al., 2014; Guo et al., 2011; Rossi et al., 2021), and inferior parietal lobe (Guo et al., 2011; Wang et al., 2009). Remarkably, these brain areas have also been extensively associated with domain-general cognitive control processes, including task switching (e.g., Dove et al., 2000), conflict monitoring (e.g., Van Veen & Carter, 2002), and response inhibition (e.g., Simmonds et al., 2008). Consistent with fMRI findings, event-related potential (ERP) studies of bilingual switching demonstrate neurophysiological patterns comparable to cognitive control. Specifically, in language switching, a higher post-stimulus N2 amplitude has been reported on switch trials compared to repeat trials (Jackson et al., 2001;

Kang et al., 2020; Verhoef et al., 2010; Zheng et al., 2020). This amplified N2 effect has also been observed in non-linguistic task switching, suggesting that greater executive control is necessary to process the more challenging switch condition compared to the less difficult repeat condition (Jamadar et al., 2015). Additionally, Zheng et al. (2020) reported a larger N2 amplitude for the run length effect, indicating that switches following a short run require more inhibitory control compared to those following a long run. In the cognition domain, this N2 effect has been reported in Go/NoGo tasks and taken as a critical indicator of response inhibition (Falkenstein et al., 1999; Jodo & Kayama, 1992; Pfefferbaum et al., 1985). Furthermore, the event-related negativity (ERN), an ERP component elicited following an error commission and theorised as a neurophysiological marker for conflict monitoring, has been reported in bilingual speech monitoring, with larger ERP amplitude reported on switch trials where participants made language selection errors compared to those with correct responses (Acheson et al., 2012; Coulter & Phillips, 2022; Zheng et al., 2018a).

Nevertheless, there is evidence in favour of the contrasting domain-specific viewpoint, implying limited overlap between the two types of control, and that language control, to some extent, operates independently (Acheson & Hagoort, 2014; Branzi et al., 2015, 2016; Calabria et al., 2012, 2015; Gray & Kiran, 2016; Magezi et al., 2012; Weissberger et al., 2012). For instance, Branzi et al. (2016) found that inhibitory control appears to play distinct roles in language control and cognitive control. In their study, Catalan-Spanish bilinguals were engaged in linguistic and non-linguistic switching tasks, where they were asked to switch between three languages (Catalan, Spanish, English) and three visual stimuli (e.g., A, big, red). The n−2 repetition cost, an index of inhibitory control, was calculated by subtracting RTs of the CBA sequences (e.g., English-Catalan-Spanish) from ABA sequences (e.g., Spanish-Catalan-Spanish). Interestingly, no correlation was observed in the n − 2 repetition cost between linguistic and non-linguistic tasks, with minimal repetition cost observed in the linguistic task. Some neuroimaging findings also indicate different functioning patterns across domains (e.g., Acheson & Hagoort, 2014; Branzi et al., 2015; Magezi et al., 2012). For example, Acheson and Hagoort (2014) directly compared ERPs related to response conflict and error monitoring (ERN and N2) in linguistic and non-linguistic tasks, finding no correlations in ERN magnitude across tasks. Similarly, Branzi et al. (2015) examined neural switch costs in both tasks and found similar involvement of the left prefrontal cortex but different activation patterns in regions such as the anterior cingulate cortex/pre-supplementary motor area in linguistic and non-linguistic tasks.

Considering the contrasting evidence, therefore, we need to be cautious when applying the “domain-general” argument. Indeed, while there are overlapping neurocognitive signals and circuits, the control processes involved with the same neural resources can be accomplished through different neural computational principles (Nozari & Novick, 2017). More converging evidence is required to comprehend this issue by targeting different neural makers or using different approaches to characterise the language network (Fedorenko & Thompson-Schill, 2014).

Midfrontal Theta Oscillations as a Window into Language Control

Neural oscillations, or brain oscillations, refer to the rhythmic or repetitive electric activity that arises in the brain as a response to stimuli. The oscillatory activity of a substantial number of neurons, that can be observed through EEG recordings, serves as a fundamental basis for human cognition, perception, and behaviours by effectively coordinating and communicating over extensive brain networks (Helfrich & Knight, 2016; Thut et al., 2012). Neural oscillations encompass various frequency bands, with theta oscillations (4–8 Hz) over the midfrontal cortex being notably considered as a compelling candidate for the engagement of cognitive control (Cavanagh & Frank, 2014; Cohen & Donner, 2013; Rawls et al., 2020). Midfrontal theta is thought to originate from the bilateral medial frontal cortex and the ACC (Asada et al., 1999; Cohen et al., 2008; Hanslmayr et al., 2008; Ishii et al., 1999; Sauseng et al., 2007; Tsujimoto et al., 2006).

Heightened midfrontal theta activity has been observed when more top-down control is required across diverse cognitive domains (e.g., Cavanagh & Frank, 2014; Cavanagh et al., 2012; Cohen & Donner, 2013; Cohen & Cavanagh, 2011; Cooper et al., 2019). In task switching, a heightened theta effect was observed in switching, as opposed to repeating, which is consistent with the RT switch cost effect (Cooper et al., 2019). Similarly, in response inhibition paradigms such as the Go/NoGo task, increased theta power was found when participants were required to withhold their response on the “No-Go” trials in comparison to the “Go” trials in which they were asked to respond (Eisma et al., 2021; Nigbur et al., 2011). Enhanced theta has been observed in action monitoring, triggered after an error is committed, in contrast to correct responses (Cavanagh et al., 2012; Luu et al., 2004). Additionally, theta activity exhibits an increase in the tasks in which top-down executive control is exerted to resolve response conflicts (e.g., Cohen & Donner, 2013; Nigbur et al., 2011; Eisma et al., 2021; Hanslmayr et al., 2008). For instance, Hanslmayr et al. (2008) tested the neural mechanisms underlying the Stroop task where participants needed to name the colour of a word when the name of the colour and the colour it was printed in are congruent (e.g., word “blue” printed in blue ink) or incongruent (e.g., word “blue” printed in red ink). Increased theta was found in incongruent trials where more control is involved due to the interference compared to congruent trials. Likewise, Cohen and Donner (2013) and Nigbur et al. (2011) found that theta activity was modulated in the Simon task where the stimulus locations and the response location are either compatible or incompatible. Theta band activity was found to be greater in incompatible conditions compared to compatible counterparts.

Considering the strong link between midfrontal theta and cognitive control, examining theta activity in bilingual switching can add to the growing body of evidence concerning the “domain-general/specific” issue. Insofar, however, no study has specifically examined the midfrontal theta oscillations in bilingual speech production, with only a limited number of investigations conducted on monolingual speakers (Krott et al., 2019; Piai et al., 2014; Shitova et al., 2017). Krott et al. (2019) and Piai et al. (2014) attempted to examine the midfrontal theta oscillations by employing picture-word interference tasks, which present target words (e.g., “dog”) to be named with three types of distractor words: semantically-related (e.g., “cat”), semantically-unrelated (e.g., “pin”), and identical (e.g., “dog”). This type of paradigm assumes the amount of competition between lexical representations of target and distractor to be larger in the semantically related condition relative to others, so more cognitive control is engaged to overcome interference. Consistently, increased theta oscillations are reported on semantically-related conditions vs. semantically unrelated and identical conditions. Similarly, Shitova et al. (2017) reported a higher level of midfrontal theta activity during Stroop-like tasks, when speech production took place in the incongruent trials with more interference to be overcome, as opposed to the congruent trials. These studies conducted in monolinguals provided support for the activation of domain-general cognitive control mechanisms in language control. Maybe add a sentence here about why bilingual control can add to this discussion (since now we are talking about monolingual control and bilingual control both as “language control”).

The Present Study

To offer a novel perspective on the nature of language control as a domain-general or domain-specific process, this study aimed to investigate the midfrontal theta oscillations in bilingual switching. The focus of the study was directed towards three language control processes – language switching, inhibitory control, and speech monitoring – which exhibit similarities to cognitive control processes, namely task shifting, inhibition, and performance monitoring (Alexander & Brown, 2010, Miyake et al., 2000). Towards this goal, I reanalysed the EEG data obtained from two previous bilingual switching studies (Zheng et al., 2020, Zheng et al., 2018a).

Both studies employed cued language switching paradigms with Dutch-English bilinguals naming pictures based on colour cues. Zheng et al. (2020) looked at inhibitory control by manipulating the number of repeat trials before a switch (i.e., run length). They found that switches after a short run (2-3 repeat trials) showed slower RT and enhanced N2 amplitude compared to the switches after a long run (5-6 repeat trials), indicating greater inhibitory control engaged in short-run switches. This suggests that as the same language is repeatedly used, the inhibition of the non-target language gradually decreases, making it easier to overcome during the switch. Slower RT and higher N2 were also found on switch trials compared to repeat trials, suggesting increased control during language switches. Zheng et al. (2018a), on the other hand, focused on speech monitoring of language selection errors. Bilinguals were found to make more language-selection errors on switch compared to repeat trials. They also observed a higher post-response ERN effect on switches with language-selection errors as compared to those with correct responses, suggesting that more top-down control is engaged after an error commission.

In this study, my focus was on the theta oscillations during the three language control processes investigated by Zheng et al. (2020) and Zheng et al. (2018). Based on previous studies supporting language control being a fully or partially domain-general process (e.g., de Bruin et al., 2014; Piai et al., 2013; Zheng et al., 2018a, 2020), I expected to observe a similar pattern of midfrontal theta modulations for cognitive control in bilingual switching. Therefore, greater theta power increase was anticipated in conditions requiring higher levels of control, specifically: switch > repeat (language switching), switches after a short run > switches after a long run (inhibitory control), and switches with language selection errors > switches with correct responses (speech monitoring). Besides, I expected the enhanced theta effect to have a midfrontal distribution, presumably reflecting the involvement of the domain-general cognitive control network.

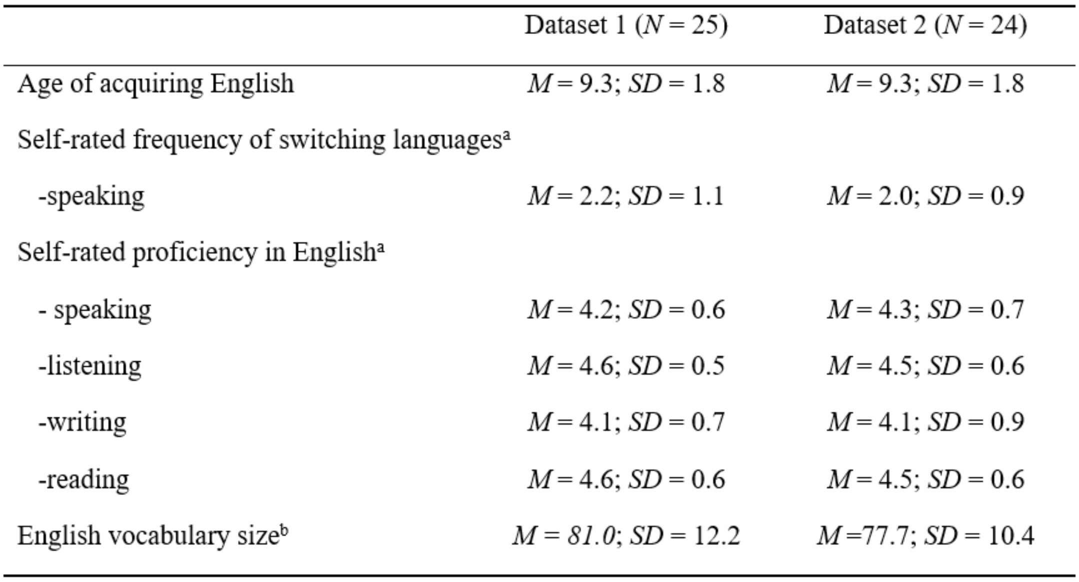
METHODS

The datasets analysed in this study were obtained from two prior publications (Zheng et al., 2020, Zheng et al., 2018a), hereafter referred to as “Study 1” and “Study 2”. The data can be freely accessed through the Donders Institute’s data repository, available at https://data.donders.ru.nl/. The two original studies adhered to the principles outlined in the Declaration of Helsinki and obtained approval from the Faculty Ethics Committee at Radboud University (ECSW2015-2311-349). The complete details of the materials and data collection procedures can be found in the original papers, while only a concise summary is provided here.

Participants and Experimental Designs

Participants were two cohorts of Dutch native bilingual speakers (dataset 1: *N* = 25, age 19–27 years, seven males; dataset 2: *N* = 24, 19–30 years, five males) who exhibited comparable English proficiency profiles, as detailed in Table 1. Participants were instructed to name pictures based on colour cues, where the colours red and yellow indicated naming in Dutch, while green and blue indicated naming in English. Both studies employed similar language switching paradigms, albeit with slight variations in their experimental designs (see Figure 1). Study 1 varied the number of repeat trials in a sequence, known as the run length, in order to potentially affect inhibitory control dynamics. This created two conditions: one with a short run length consisting of 2-3 consecutive repeat trials, and another with a long run length

Table 1. Participant English Proficiency Profile.



	Dataset 1 (*N* = 25)	Dataset 2 (*N* = 24)
Age of acquiring English	*M* = 9.3; *SD* = 1.8	*M* = 9.3; *SD* = 1.8
Self-rated frequency of switching languages[a]		
-speaking	*M* = 2.2; *SD* = 1.1	*M* = 2.0; *SD* = 0.9
Self-rated proficiency in English[a]		
- speaking	*M* = 4.2; *SD* = 0.6	*M* = 4.3; *SD* = 0.7
-listening	*M* = 4.6; *SD* = 0.5	*M* = 4.5; *SD* = 0.6
-writing	*M* = 4.1; *SD* = 0.7	*M* = 4.1; *SD* = 0.9
-reading	*M* = 4.6; *SD* = 0.6	*M* = 4.5; *SD* = 0.6
English vocabulary size[b]	*M = 81.0*; *SD* = 12.2	*M* =77.7; *SD* = 10.4

Note. M = Mean; *SD* = Standard Deviation.

[a]Self-ratings ranged from 1 (rare/bad) to 5 (often/good).

[b]English vocabulary size was measured with the LexTALE test (Lemhöfer & Broersma, 2012).

comprising 5-6 consecutive repeat trials. In Study 2, participants underwent a speed training session before the experiment began, and the time limits were presented and calibrated per participant, including feedback on their response speed, with the intention of inducing more speech errors.

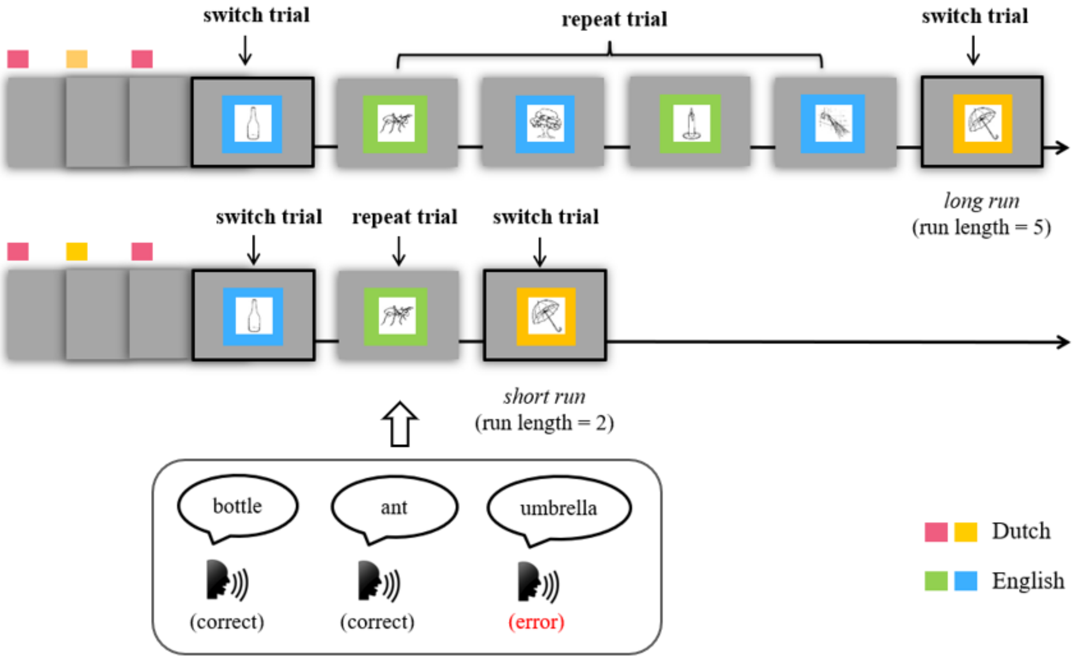


Figure 1. Experimental designs. Study 1 manipulated the run length before switch trials, creating short runs (2-3 consecutive repeats) and long runs (5-6 consecutive repeats) to investigate inhibitory control. Study 2 implemented time pressure on participants, deliberately inducing more speech errors, as shown in the rectangular graph.

EEG Acquisition

A consistent EEG data acquisition protocol was used for both studies, involving continuous recording of EEG data at 500 Hz with a band-pass filter of 0.016–125 Hz. Fifty-seven active Ag–AgCl ring electrodes were used following the international 10-20 standard, maintaining impedance below 20 kΩ. The left mastoid served as the online reference. To facilitate visual inspection, bipolar electrooculograms (EOGs) were recorded with vertical EOG (EOGV) electrodes above and below the right eye, and horizontal EOG (EOGH) electrodes on the left and right temples. Electromyographic (EMG) activities were recorded with electrodes on the upper lip and throat.

Data Analysis

Data reanalysis focused on three language processes: language switching (in both Study 1 and Study 2), inhibitory control (in Study 1), and error monitoring (in Study 2). Correspondingly, three specific comparisons were performed: switch trials vs. repeat trials, switch trials following short runs vs. switch trials following long runs, and switch trials with language selection errors vs. switch trials with correct responses.

Behavioural Analysis

To serve as a comparison to EEG results, the behavioural data analysis was replicated from the original studies, with modifications to the included variables. In both original studies, participants' RTs during picture naming were recorded and manually corrected offline. Responses were categorized as correct or speech errors, Speech errors included language-selection errors (e.g., saying the Dutch word "paraplu" instead of the English equivalent "umbrella") and other types of errors (e.g., self-corrections and disfluencies). RT and error rate were compared for two sets of conditions (switch vs. repeat trials for language switching, switches after short runs vs. long runs for inhibitory control). RT analyses excluded speech error trials and post-error trials. All the trials at the beginning of each block were also excluded since they do not involve switch or repeat conditions. For inhibitory control conditions (short run vs long run), all the runs with error trials were also excluded because an error response can change the nature of the subsequent trial, for example, converting a long run into a short run. Likewise, error rate analyses excluded the trials at the beginning of each block and post-error trials for both sets of conditions. All the runs with errors were excluded solely for inhibitory control conditions.

Behavioural data underwent statistical analyses using version 1.1.26 of the lmer4 package (Bates et al., 2014) within R software (R Core Team, 2023). I performed a generalised mixed-effects model of RTs as a function of conditions, incorporating random slopes of condition for participants and pictures, as well as random intercepts for both participants and pictures (see Appendix). An analogous analysis was conducted for error rate using binomial family (see Appendix). Considering error monitoring and RT reflect distinct processes, where error monitoring pertains to error detection whilst RT relates to the efficiency of motor response execution, it would be less informative to directly compare RTs for error monitoring. Instead, I computed percentages for error trials relative to total trials and for language-selection errors relative to error trials in both switch and repeat conditions.

EEG Preprocessing

To enhance scalp and source level analysis of theta band oscillations, I re-preprocessed the raw EEG data using the open-source toolbox Fieldtrip (Oostenveld et al., 2011) in MATLAB (R2022a, The Math Works, Inc). Stimulus-locked analysis was employed to explore oscillations linked to language switching (switch vs repeat) and inhibitory control (short run vs long run). Response-locked analysis was utilized to investigate the oscillations associated with error monitoring (language-selection errors vs correct responses). Consequently, stimulus-locked analysis was conducted on both datasets, while response-locked analysis was exclusively performed for Study 2. The preprocessing pipeline is described as follows: the data were initially segmented into long, stimulus-locked epochs for analysis. For Study 1, the epochs spanned from -750 ms to 1500 ms relative to picture onset; for Study 2, the epochs encompassed from -750 ms to 2500 ms relative to picture onset. This step aimed to facilitate the later conducted Independent Component Analysis (ICA) process and include the response-locked data for study 2. After segmentation, the data were re-referenced to linked mastoid and band-pass filtered between 0.1 Hz and 40 Hz. To effectively eliminate eye artifacts (e.g., eye blinks, lateral eye movements), an independent component analysis (ICA) approach was employed, and two rounds of visual artifact rejection were conducted in relation to the ICA process. The first round was performed prior to ICA to discard prominent artifacts that could potentially interfere with the ICA results such as head movements and technical artifacts. Bad channels that exhibited significant disturbances were also excluded from the analysis during this phase. Following the ICA, the second round of artifact rejection was conducted to further eliminate any residual artifacts that might have remained (e.g., muscle artifacts). Prior to the second round of artifact rejection, the cleaned data from Study 2 underwent specific segmentation to cater to stimulus-locked analysis (epochs from -750 ms to 1500 ms relative to picture onset) and response-locked analysis (epochs from -750 ms to 1000 ms relative to vocal response). For the later conducted scalp-level analysis, any excluded individual channels were interpolated using neighbouring channels. On average, 2.1% of the stimulus-locked data and 0.4 channels per participant were discarded for Study 1; 2.9 % of the stimulus-locked data, 4.6 % of the response-locked data and 1.6 channels per participant were discarded for Study 2.

Scalp-Level EEG Analysis

Time-frequency representations (TFRs) were computed for both stimulus-locked and response-locked data using a fixed-length window Hanning taper technique. A time window of 500 ms was used, and the analysis involved sliding windows with 50 ms time steps and 2 Hz frequency steps, covering the frequency range of interest from 2 Hz to 20 Hz. Time-resolved power spectra were computed for stimulus-locked data from -500 ms to 1500 ms relative to the stimulus onset, and for response-locked data from -500 ms to 1000 ms relative to the response onset. Consistent with the behavioural analysis, trials at the beginning of each block and post-error trials were excluded from all analyses. In both the language switching (switch vs. repeat) and inhibitory control (short run vs. long run) analyses, any error trials were omitted from the analysis. Additionally, for the inhibitory control comparison, runs containing error trials were also excluded. I then computed power estimates for each participant under three sets of conditions: switch trials vs. repeat trials, switch trials following short runs vs. those following long runs, and switch trials following language selection errors vs. those with correct responses. Finally, I averaged the TFRs for each condition across participants, resulting in a grand-averaged representation.

Source-Level EEG Analysis

To investigate the origin of the theta effects observed in the sensor-level analysis (as mentioned in the Results), source localization was performed to map the two-dimensional scalp-level EEG data onto the three-dimensional cortical structures. Based on the time window capturing the theta effects at the scalp-level, the source-level analysis was performed within two specific time intervals of interest (i.e., 200 ms to 700 ms post picture onset for language switching effect in Study 1 and 0 ms to 500 ms post response onset for both language switching and error monitoring effect in Study 2). Interpolated channels during scalp-level analysis were discarded in the analysis, and a common average reference was applied to enhance the spatial resolution and the accuracy of source localization. To construct a volume conduction model, we employed the Boundary Element Method (BEM) using a standard MRI template known as Montreal Neurological Institute (MNI) template and template 3D electrodes that were matched with the BEM model. Subsequently, the brain volume was depicted as a grid with a 1 cm resolution. I employed a frequency domain beamforming technique known as DICS (Gross et al., 2001) to estimate the activity at the source level. Lead field matrices were computed for each grid point. The cross-spectral density matrix was centred at 6 Hz and smoothed with a 2 Hz window to obtain the cross-spectral density matrix within the theta band (4-8 Hz). These matrices were then utilized to calculate common spatial filters for both conditions combined (switch and repeat for language switching, short and long run for inhibitory control). These filters were subsequently applied to transform the sensor-level data into source-level spectral power estimates for each grid point, separately for each condition.

Statistical Testing and Power Masking

On the sensor level, non-parametric cluster-based permutation tests were conducted to evaluate the difference of theta oscillations between conditions (Maris & Oostenveld, 2007).

Spatial-spectral-temporal data (time, frequency, channel) was generated in three-dimensional spaces. Dependent samples *t*-tests were performed on the spatial-spectral-temporal data points within the theta band (4-8 Hz) to assess mean differences between conditions across frontal central channels. Full post-stimuli time windows of 0-700 ms and 0-500 ms were employed for stimulus-locked and response-locked data analyses, respectively. All neighbouring datapoints that exceeded the cluster-forming threshold (alpha = 0.05) were grouped into clusters, and the *t*-statistics within each cluster were summed into a cluster-based permutation statistic. Next, the Monte Carlo approximation algorithm was used to randomly partition the trial data across conditions 1000 times within participants, and the largest cluster-based *t*-statistics calculated for each random partition were grouped into a Monte Carlo permutation distribution. This permutation distribution was then compared against the calculated cluster-based permutation statistic, with the clusters that exceeded the 2.5th percentile or fell below the 2.5th percentile of the permutation distribution were deemed statistically significant. On the source level, a threshold-based approach combined with a power mask was used for visualization purposes to highlight meaningful theta power modulations.

RESULTS

Study 1

Behavioural Results

Language switching. Figure 2 (upper panel) displays the median RTs and error rates for switch vs. repeat trials for Study 1. Participants responded slower on switch trials (M = 973, SD = 279) compared to repeat trials (M = 867, SD = 276), suggesting a significant switch cost effect [β = 96.6, SE = 2.54, t = 37.97, p < .001]. Additionally, participants made more errors on switch trials (M = 6.18%, SD = 2.29%) compared to repeat trials (M = 3.02%, SD = 1.36%) [β = 0.72, SE = 0.13, z = 5.57, p < .001].

Inhibitory control. Figure 2 (lower panel) illustrates the median RTs and error rates for switches after short runs vs. switches after long runs. Participants responded slower on switch trials following a short run (M = 987, SD = 290) as compared to those following a long run (M = 950, SD = 271) [β = 40.74, SE = 10.42, t = 3.91, p < .001]. They also made more errors on switches following short runs (M = 6.96%, SD = 3.28%) compared to long runs (M = 4.87%, SD = 2.76%) [β = 0.30, SE = 0.20, z = 1.47, p = .016].

Scalp-Level Results

Language switching. Figure 3(A) left panel depicts the power difference between switch and repeat trials within the 2-12 Hz frequency range, time-locked to the picture onset from -200 to 700 ms, over frontocentral channels. A statistically significant difference between switch and repeat conditions (p = .028) was detected between 0-700 ms post stimulus in the theta band (4-8 Hz) by employing a cluster-based permutation test. The effect was particularly prominent in two distinct clusters: one was observed between 100 and 250 ms after the stimulus onset and centred around 6-8 Hz, and another identified between 350 and 450 ms post-stimulus and was centred around 4-6 Hz. Figure 3(A) right panel features a scalp topographical map that encompasses both clusters, clearly showing the effect in the central sensors.

Inhibitory control. Figure 3B shows power difference between switch trials following a short run versus a long run within the 2-12 Hz frequency range, measured between -200 and 700 ms relative to the picture onset over frontocentral channels. However, there was no statistically significant difference found between the short and long run conditions in the theta band (4-8 Hz) within the time window of 0-700 ms post picture onset (p = .695).

Source Localization

For Study 1, source-level analyses were solely performed for language switching conditions due to the presence of significant TFR results. Figure 4 presents the sources for the contrast between switch and repeat trials within the theta band (4-8 Hz) and the time window that encompasses the duration identified in the scalp-level analysis (0-500ms). The estimated sources were predominantly localized within the frontal left hemisphere, as depicted in the figure.

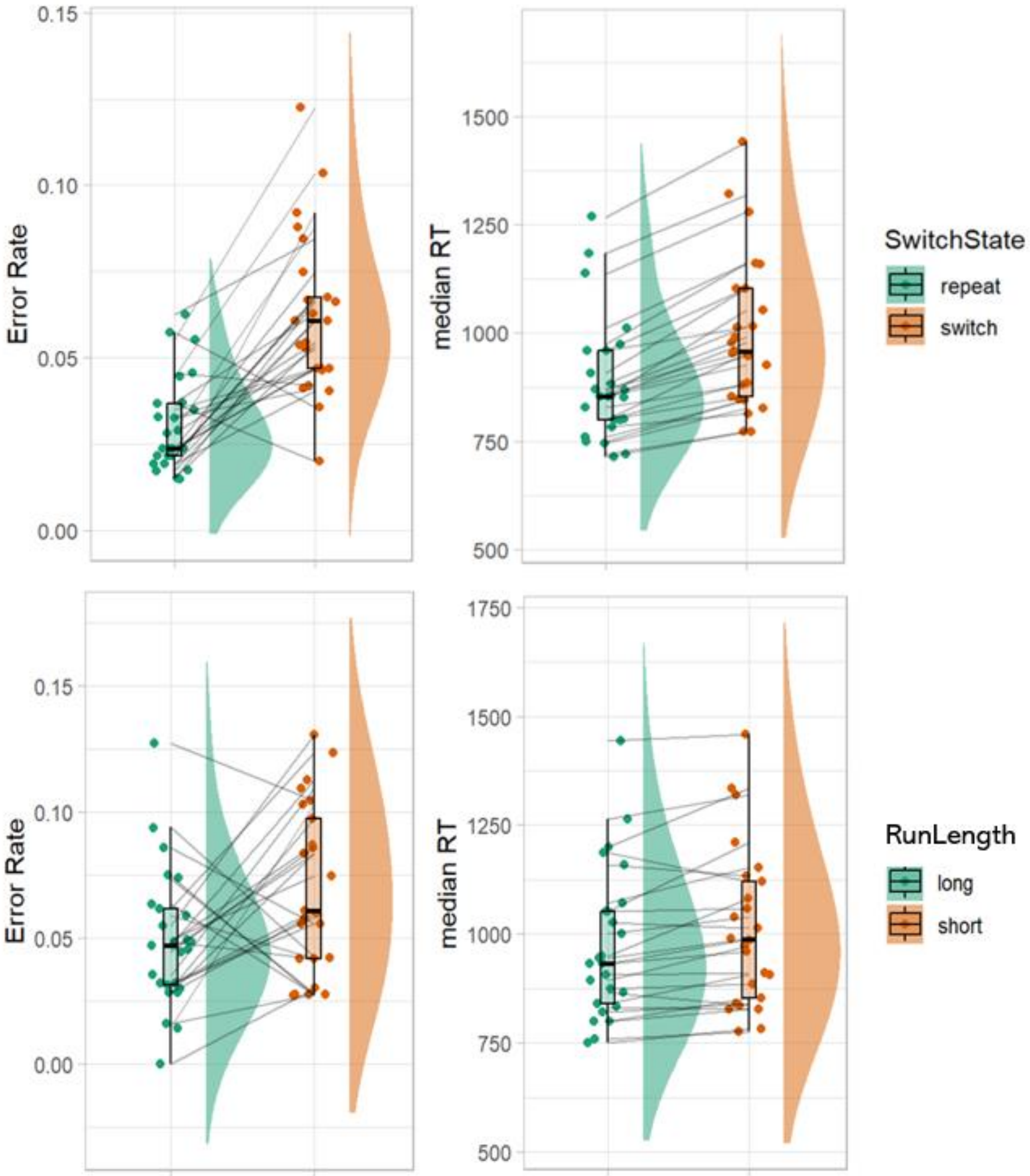


Figure 2. Behavioural results for Study 1. The upper panel shows the raincloud plots of participants' error rates and median RTs for language switching conditions (switch trials vs. repeat trials). The lower panel presents shows the raincloud plots of participants' error rates and median RTs for inhibitory control conditions (switches after a short run vs. switches after a long run). The density plot depicts the distribution of data across participants. For the boxplot, the bottom edge of the box corresponds to the first quartile, and the top edge represents the third

quartile, The line inside the box represents the median of the data. The individual data points represent individual observations.

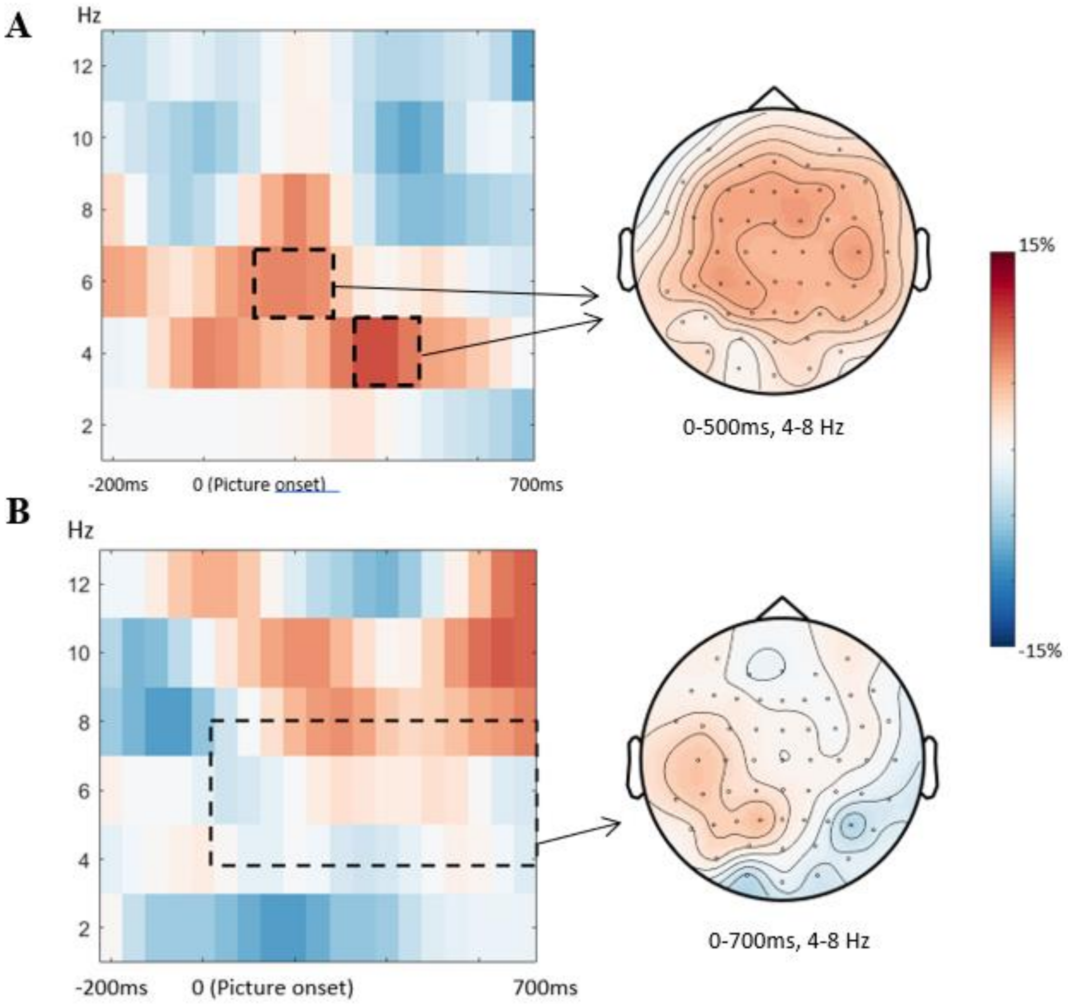


Figure 3. Results of TFR results for langauge switching and inhibitory control conditions in Study 1. **A.** Left panel shows the stimulus-locked time-resolved spectrum of the contrast between switch versus repeat trials, averaged over 15 frontocentral channels: F3, F1, Fz, F2, F4, FC3, FC1, FCz, FC2, FC4, C3, C1, Cz, C2, C4. The right panel shows the topography of the contrast (switch vs. repeat) in the theta band (4-8 Hz) between 0 and 500 ms post picture onset. **B.** The left panel shows the stimulus-locked time-resolved spectrum of the contrast between switch trials following a short run vs. those following a long run over the same cluster of frontocentral channels. The right panel depicts the topography of the contrast in the theta band (4-8 Hz) between 0 and 700 ms post picture onset, as indicated in the dashed line.

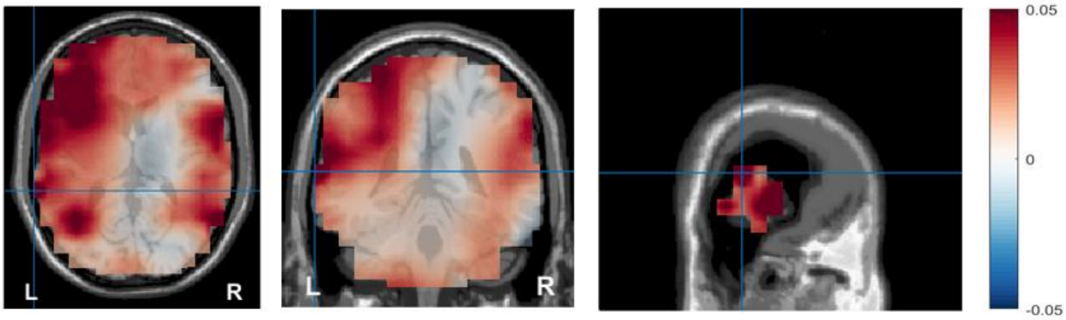


Figure 4. Estimated sources in the theta band (4-8 Hz) for language switching (time window of 0-500ms) in Study 1. The opacity map shows the source difference between switch and repeat trials, with the higher intensity values presented as opaque and the lower intensity values as transparent. The left, middle, and right panels display the corresponding horizontal, coronal, and sagittal slices of the estimated sources, respectively. Colour bar indicates the t-values for individual grid points.

Study 2

Behavioural Results

Language switching (replication). The language switching analysis was replicated in Study 2 to validate the results across studies. As shown in Figure 5, similar results were found for picture naming performance, where participants responded slower on switch trials (*M* = 752, *SD* = 191) compared to repeat trials (*M* = 640, *SD* = 142) [β = 84.82, *SE* = 4.53, *t* = 18.73, *p* < .001]. More errors were also observed on switch trials (*M* = 44.45%, *SD* = 12.11%) compared to repeat trials (*M* = 13.76%, *SD* = 4.88%) [β = 1.62, *SE* = 0.12, *z* = 13.14, *p* < .001].

Error Monitoring. Out of all the switch trials, 44.4% resulted in errors, while 55.6% were correct responses. Within the error trials, 83.9% were language-selection errors.

Scalp-Level Results

Language switching (replication). Similar patterns of power changes between switch and repeat trials were observed during language switching in Study 2. Figure 6(A) left panel illustrates the power changes within the 2-12 Hz frequency range over frontocentral channels, between -200 ms to 700 ms relative to the picture onset. A statistical analysis confirms a significant increase in theta power (4-8 Hz) in the frontocentral sensors between switch and repeat conditions from 0 to 700 ms post-stimulus (*p* = .002). The effect is most pronounced between 200-600 ms post stimulus, clustered around 4-6 Hz. The topographical map in Figure 6(A) right panel reveals that the effect is primarily distributed in the frontocentral region.

Error monitoring. The power difference between switch trials with language selection errors and switch trials with correct responses is displayed in Figure 6(B) left panel, within the 2-12 Hz frequency range and time-locked to the response onset from -200 ms to 700 ms, averaged over frontocentral channels. A statistically significant theta power increase was detected in switch trials with language selection errors compared to those with correct responses within the time window of post response onset (*p* = .002). The effect exhibited its greatest prominence within the 4-6 Hz frequency range, commencing from the moment of the response and extending up to 400 ms thereafter. The scalp topographical map presented in Figure 6(B) right panel demonstrates that the effect primarily manifests in the frontocentral channels.

Source Localisation

Language switching (replication). Source-level analysis was carried out to compare the language switching conditions in Study 2, focusing on the theta band (4-8 Hz) and a time window that aligned with the duration identified in the scalp-level analysis (200-700 ms). The outcomes are presented in Figure 7 (upper panel). Surprisingly, the estimated sources were predominantly found in the posterior left hemisphere. The reasons for the unexpected result are discussed in the Discussion.

Error Monitoring. Source-level analysis for error monitoring focused on the theta band of 4-8 Hz and the time window covering the period observed in the scalp-level analysis (0-500ms), with the results shown in Figure 7 (lower panel). Unexpectedly, the estimated sources show a clear predominance in the right hemisphere, with notable localization in both the frontal and posterior regions, which will be discussed further in the Discussion.

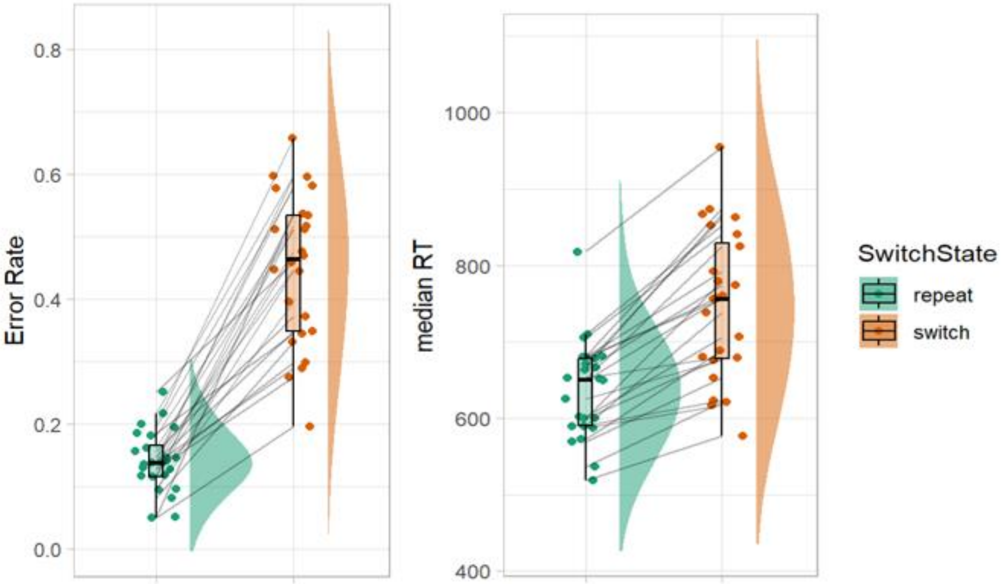


Figure 5. Raincloud plots illustrating the error rates (left) and median RTs (right) of participant picture naming for language switching (switch vs. repeat trials) in Study 2. The density plot

depicts the distribution of data across participants. For the boxplot, the bottom edge of the box corresponds to the first quartile, and the top edge represents the third quartile. The line inside the box represents the median of the data. The individual data points represent individual observations.

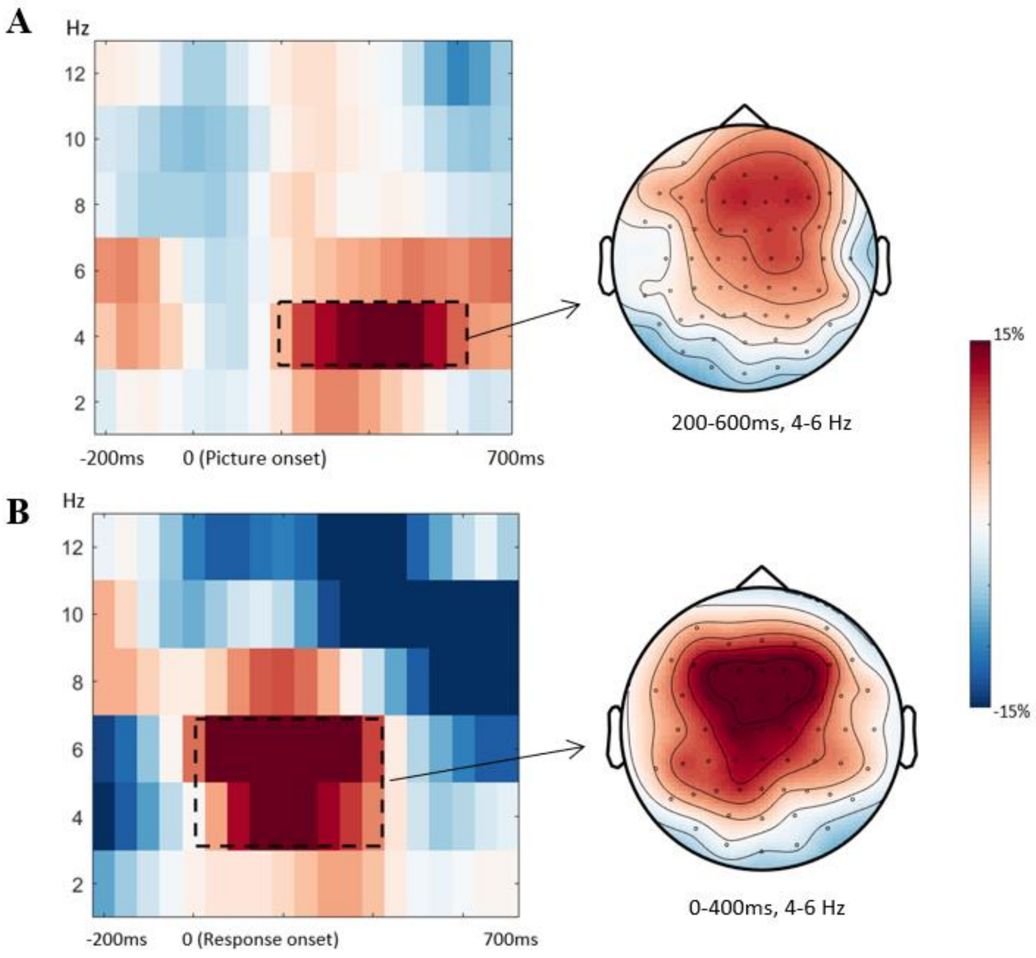
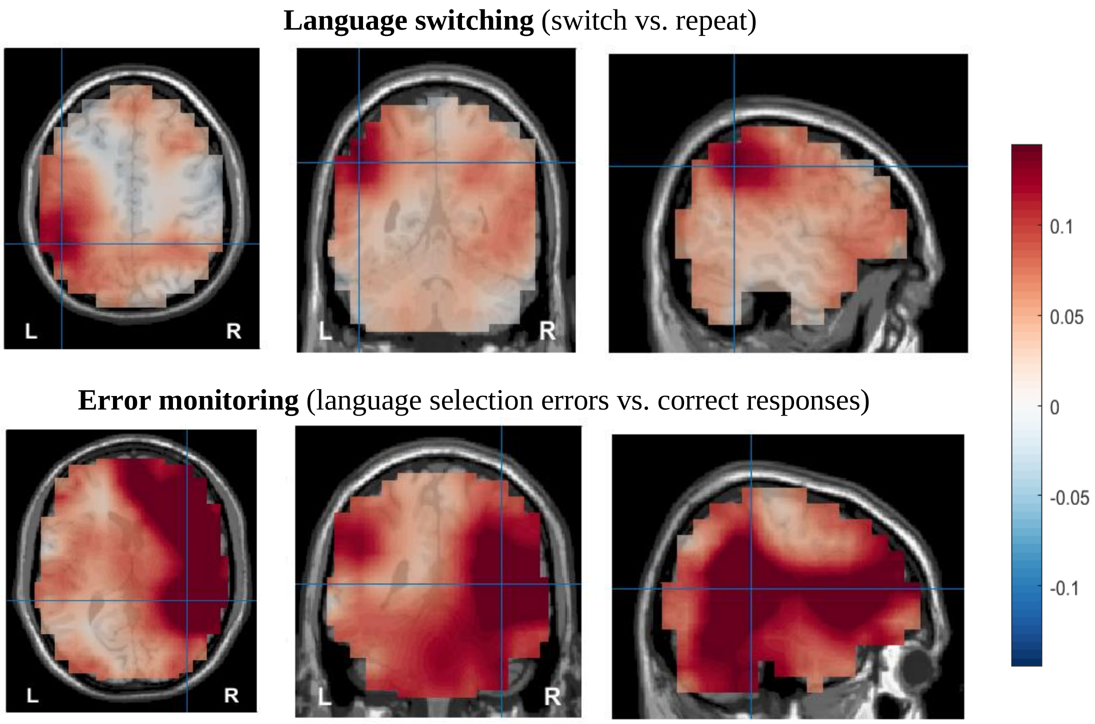


Figure 6. Results of TFR results for langauge switching and error monitoring conditions in Study 2. **A.** Left panel shows the stimulus-locked time-resolved spectrum of the contrast between switch versus repeat trials, averaged over 15 frontocentral channels: F3, F1, Fz, F2, F4, FC3, FC1, FCz, FC2, FC4, C3, C1, Cz, C2, C4. The right panel shows the topography of the contrast (switch vs. repeat) in the theta band (4-6 Hz) between 200 and 600 ms post picture onset (see the dashed line in the left panel). **B.** The left panel depicts response-locked time-resolved spectrum revealing the contrast between switch trials with language selection errors and switch trials with correct responses over the same cluster of frontocentral channels. The right panel of the figure showcases the topography of the contrast within the frequency range of 4-6 Hz during the time period spanning from 0 to 400 ms after the response onset, as indicated by the dashed line.



Language switching (switch vs. repeat)

Error monitoring (language selection errors vs. correct responses)

Figure 7. Estimated sources in the theta band (4-8 Hz) for language switching (time window of 200-700ms) and error monitoring (time window of 0-500ms) in Study 2. The upper panel presents the opacity map for the contrast between switch and repeat trials, and the lower panel illustrates another opacity map for the contrast between switches following language-selection errors and those with correct responses. The higher intensity values are presented as opaque and the lower intensity values are as transparent. For each contrast, the left, middle, and right panels display the corresponding horizontal, coronal, and sagittal slices of the estimated sources, respectively. Colour bar indicates the t-values for individual grid points.

DISCUSSION

Language control in bilingual speakers involves proficiently switching between languages, inhibiting interference from the non-target language, and continuously monitoring speech errors. These control processes seem to share similarities with executive functions observed outside of linguistic contexts, particularly in tasks such as task switching, inhibitory control, and action monitoring (Alexander & Brown, 2010; Miyake et al., 2000). In recent years, there has been considerable attention devoted to the question of whether language control is predominantly governed by the domain-general cognitive control mechanisms that regulate various executive functions in non-linguistic domains, or if it operates independently under a domain-specific linguistic network (e.g., Nair et al., 2021; Niendam et al., 2012). This issue remains a subject of controversy, as some behavioural and neuroimaging evidence supports a shared mechanism for language control and cognitive control (e.g., Abutalebi et al., 2008; Alario et al., 2006; Coderre et al., 2016; de Bruin et al., 2014; Declerck et al., 2017a; Zheng et al., 2018a, 2020), while other, contrasting evidence suggests their distinct separation (e.g., Acheson & Hagoort, 2014; Branzi et al., 2015, 2016; Calabria et al., 2012, 2015; Gray & Kiran, 2016). The heightened midfrontal theta oscillations have been recognized as a neural indicator associated with improved cognitive control (e.g., Cavanagh & Frank, 2014; Cavanagh et al., 2012; Cohen & Donner, 2013). Exploring whether similar theta power modulations are likewise present in bilingual language control processes can offer valuable insights into the relationship between language control and cognitive control, thereby contributing additional empirical evidence to the ongoing debate. Hence, the goal of this study was to explore midfrontal theta oscillations in bilingual switching, with a specific focus on three fundamental control processes: language switching, inhibitory control, and error monitoring. To achieve this, I reanalysed the EEG data from two previous bilingual switching studies (Zheng et al., 2020, Zheng et al., 2018a).

Midfrontal Theta in Language Control Processes

For language switching, we observed consistent midfrontal theta oscillation patterns in both original datasets: switch trials exhibited midfrontal theta power increase compared to repeat trials, with this enhancement being predominantly distributed in the frontal-central region. The observed results are in line with our hypothesis and the behavioural observation that participants exhibited poorer picture naming performance (i.e., slower RT and higher error rates) during switch trials compared to repeat trials. This finding is consistent with prior research on non-linguistic task switching, which reported an increase in theta power during preparation for task switching compared to task repetition (Cooper et al., 2019). This suggests a shared neurophysiological pattern for switching across both linguistic and non-linguistic domains. Furthermore, our findings are in line with previous behavioural evidence that reported a closely matched switch cost effect between linguistic and non-linguistic tasks (Declerck et al., 2017; Prior & Gollan, 2013; Timmermeister et al., 2020). They also align with fMRI studies demonstrating shared neural circuits engaged during language and task switching (e.g., Abutalebi & Green, 2008; de Bruin et al., 2014; Guo et al., 2011; Wang et al., 2009), as well as ERP studies consistently reporting heightened N2 effects during language/task switches compared to repeats (Jackson et al., 2001; Kang et al., 2020; Verhoef et al., 2010; Zheng et al., 2020). Consequently, our results contribute to the growing empirical evidence supporting the involvement of domain-general cognitive control mechanisms in language switching process.

Similarly, in error monitoring, we observed an increase in midfrontal theta power during switch trials following language selection errors compared to those with correct responses, which is consistent with our hypothesis. This finding also corresponds to the presence of midfrontal theta patterns observed in error commission during action monitoring tasks (Cavanagh et al., 2012; Luu et al., 2004), indicating a shared neurophysiological marker for selection errors across both linguistic and action domains. Furthermore, the results support studies reporting the language switching training effect in action monitoring tasks (Liu et al., 2019) and neuroimaging studies that have identified shared neural mechenisms for speech monitoring and conflict/error monitoring, such as the ACC (Abutalebi et al., 2012; Christoffels et al., 2007; Gauvin et al., 2016) and ERN component (Acheson et al., 2012; Coulter & Phillips, 2022; Zheng et al., 2018a). Taken together, the results suggest that speech monitoring of language selection errors relies on the activation of domain-general cognitive control mechanisms.

Contrary to our hypothesis, however, we did not observe midfrontal theta modulations in the inhibitory control process related to the run length effect – no theta power difference between switches after a short run compared to switches after a long run. This contradicts the behavioural results, which showed inferior picture naming performance in short-run switches than long-run switches. This result also contradicts the findings of the original study conducted by Zheng et al. (2020), which employed the same dataset and reported a larger N2 amplitude, another indicator of heightened inhibitory control, during short-run switches. Moreover, it goes against the fMRI studies supporting the existence of shared neural circuits associated with inhibition across domains (de Bruin et al., 2014; Rossi et al., 2021), as well as the prior investigations of inhibition in non-linguistic tasks, where increased theta-band modulations were observed in situations requiring greater top-down control (Eisma et al., 2021; Nigbur et al., 2011). Hence, this finding does not support the notion of inhibitory control being domain-general in bilingual switching. One potential explanation is that inhibition in language control operates through a distinct mechanism that differs from cognitive control. This perspective can be found in Branzi et al.'s (2016) study indicating a dissociation in inhibitory control between language switching and non-language switching tasks. In their study, the n-2 repetition cost, serving as a measure of inhibitory control, was computed for both tasks. The outcomes revealed that the linguistic task displayed negligible repetition cost, which did not correlate with the cost observed in the non-linguistic task. This perspective might also explain why some studies have not consistently observed bilingual advantages in inhibitory control tasks (Paap & Greenberg, 2013; Von Bastian et al., 2016).

Besides the assumption that inhibitory control operates differently in cognitive control and language control, the lack of midfrontal theta oscillations in relation to the run-length effect could also imply that the run-length effect is not primarily driven by the inhibition of the non-target language but the enhancement of the target language (Allport & Wylie, 1999; Philipp et al., 2007). As individuals repeatedly use the same language, the enhancement of the target language diminishes, resulting in a reduced need for control when switching to another language. However, as also asserted by Zheng et al. (2020), we believe that whether inhibition or enhancement is at play, both mechanisms still reflect a form of top-down control. Thus, if midfrontal theta reflects general-purpose cognitive control process, it should also reflect enhancement. The full understanding of this run length effect observed in bilingual switching remains uncertain and subsequent studies could delve into exploring the underlying mechanisms driving this phenomenon.

Methodological Reflections

In the present study, some methodological reflections are worth considering. First, the source-level findings displayed inconsistencies with the scalp-level results. Specifically, the theta effect in language switching was observed in the frontal and posterior left hemisphere, and the theta effect related to error monitoring was localized in both the frontal and posterior regions of the right hemisphere. The source-level findings are likely unreliable due to the absence of individual subjects' anatomical scans, opting instead for a standard MRI template that disregards inter-subject variability. Additionally, using a template for electrode placements may have introduced errors in estimating the sources, as it does not consider significant variations in electrode placement. It was also considered that the repairment of rejected channels (with an average of 0.4 and 1.6 channels being rejected per participant for Study 1 and Study 2, respectively) solely conducted at the scalp level could potentially explain the discrepancies observed between the results obtained at the scalp level and those at the source level. However, upon further examination, it became evident that the unexpected results (i.e., reversed lateralization) at the source level did not result from the missing channels.

Second, the divergent findings pertaining to the N2 component and midfrontal theta oscillations observed in the same dataset of Zheng et al. (2020), both of which serve as neuropsychological markers for inhibitory control, lead us to postulate that these markers reflect distinct neural processes (Cohen & Donner, 2013). In non-linguistic domains, some studies have reported limited and nonsignificant associations between ERP and oscillatory measures linked to conflict resolution (Cavanagh et al., 2012) and feedback processing (Cohen et al., 2007). Thus, ERP and neural oscillation analyses appear to offer complementary insights into language control processes.

Third, we need to be cautious interpreting the presence of a midfrontal theta effect in language switching and error monitoring processes, as midfrontal theta may not represent a unified cognitive control mechanism and could originate from multiple sources (Zuure et al., 2020). In a recent investigation conducted by Messel et al. (2021), utilizing a cued stop-signal task, distinct neural circuits were found to be associated with cue-locked and response-locked theta activity. Hence, similar midfrontal theta modulations observed in both language control and cognitive control processes may still be governed by different neural networks. Utilizing both fMRI and EEG techniques in future studies would be advantageous for understanding shared or distinct neural mechanisms distinguished by midfrontal theta activity during language and cognitive control.

Conclusion

In summary, as the initial endeavour to examine midfrontal theta oscillations in bilingual switching, we observed midfrontal theta power increase during language switching, specifically in switch trials compared to repeat trials, as well as during speech error monitoring in switches with language-selection errors compared to those with correct responses. The pattern of midfrontal theta resembles that reported in executive functions like task switching and action monitoring, thus supporting the activation of domain-general cognitive control mechanism in language control. We failed to observe the midfrontal theta effect in short-run switches compared to long-run switches, indicative of an inhibitory control process. This suggests inhibitory control might operate differently between the linguistic and non-linguistic domain, aligning with the domain-specific language control perspective. Alternatively, the run length effect during bilingual switching might not be primarily governed by the inhibition of the non-target language.

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Appendix

Linear Mixed Effect Models

Study 1 – language switching

```
# RT for switch vs repeat
glmer.runlength.RT.all <- glmer(RT_corrected ~ Rlposthoc + (1 + Rlposthoc | pNumber) + (1
+ Rlposthoc | PicNam),
data = mydata.runlength.RT.all,
family = Gamma(link = "identity"),
control = glmerControl(optimizer = 'bobyqa'))
```

```
# error rate for switch vs repeat
glmer.swicost.error.all <- glmer(IsErrorInclRTout ~ SwitchState + (1 + SwitchState |
pNumber) + (1 + SwitchState | PicNam),
                        data = mydata.swicost.error.all,
                        family = binomial)
```

Study 1 – inhibitory control

```
# RT for switches after a short run vs a long run
glmer.runlength.RT.all <- glmer(RT_corrected ~ Rlposthoc + (1 + Rlposthoc | pNumber) + (1
+ Rlposthoc | PicNam),
                        data = mydata.runlength.RT.all,
                        family = Gamma(link = "identity"),
                        control = glmerControl(optimizer = 'bobyqa'))
```

```
# error rate for switches after a short run vs a long run
glmer.runlength.error.all <- glmer(IsErrorInclRTout ~ Rlposthoc + (1 + Rlposthoc |
pNumber) + (1 + Rlposthoc| PicNam),
                         data = mydata.runlength.error.all,
                         family = binomial)
```

Study 2 – language switching

```
# RT for switch vs repeat
glmer.swicost.RT.all <- glmer(RT_corrected ~ SwitchState + (1 + SwitchState | pNumber) +
(1 + SwitchState| PicNam),
                        data = mydata.swicost.RT.all,
                        family = Gamma(link = "identity"),
                        control = glmerControl(optimizer = 'bobyqa'))
```

```
# error rate for switch vs repeat
glmer.swicost.error.all <- glmer(IsError ~ SwitchState + (1 + SwitchState | pNumber) + (1 +
SwitchState| PicNam),
                          data = mydata.swicost.error.all,
                          family = binomial)
```